Production process development of adhesive dispensing with focus on cost and quality

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ABSTRACT

In our society, digital cameras are used for a countless number of different purposes. There are many components going in to making such a complex product but one could argue that the camera sensor and lens make out the heart of a digital camera. Axis Communications AB, founded in 1984, is a Swedish company which pioneered and specialize in digital network cameras. In 1996 Axis delivered the first network camera to the market and has remained a leading actor in the field ever since. The thesis focus on one of the fixed focus cameras in Axis assortment called Hedwig. In Hedwig, the lens and sensor are bonded using adhesive were the dispensing of the adhesive both drive costs and quality due to high variations in precision and quantity.

The thesis focuses on the adhesive dispensing process and assembly of the optical module in Hedwig. There are three main focus areas; minimizing the use of adhesive, controlling the bonding process for repeatable results and investigating if a new adhesive can be introduced. To be able to analyze this, Axis acquired a high precision automated dispensing system. The system, if fully implemented on all production sites is considered a big investment and hence a production cost analysis was done to see how the production cost is affected by the automated system.

To start, the current production has been mapped and data and information gathered. The authors visited the production and analyzed the current production. The current production generates variable quality and through six sigma analysis it was gathered that the sigma levels were in general at level 2, except in one process step. The module cost was uncertain due to lack of existing economic data and production statistics relevant for the optical module. Analysis of current production shows that adhesive amount varies a lot between modules and excessive use to compensate for inaccuracy in the manual dispensing process. All parts are weighed to assure adhesive amount is within allowed interval. Push-out tests are used to validate that the curing is done correctly. It makes out 6,8% of the calculated module cost.

A series of test were performed using the new automated system to see what results could be achieved. The dispenser tolerance was high enough to allow the adhesive weighing to completely be removed. Test results conclude that the quantity of adhesive used have small effect on the quality. On the other hand, the position and curing has great impact on the quality of the bond. From the tests, the sigma levels were all increased to 4, resulting in a theoretical yield greater than 99,7%.

It has been shown that an automated dispenser could efficiently be introduced into the current production. Production cost can be lowered by as much as 13% if the all the proposed cost savers were implemented. The cost reduction is due to the removal of unnecessary production steps, decreasing the use of adhesive and removing the push out testing.

Key words: Adhesive dispensing, Six Sigma, production development, cost based decision making.

PREFACE

This thesis is the final examining part of a five year long Master of Science education preformed at LTH. The thesis is 30 credits and was written from January to June 2017.

The authors would like to issue a great thank you to Axis Communications for making this thesis possible. Thanks to the DFA team and other helpful employees at operations for, taking interest, making time to help and support the authors on all questions. A special thanks to the thesis supervisors, Helena Wedin and Thomas Elfström, for their support and guidance. Thomas Elfström should also be noted for technical and theoretical support regarding adhesives and laboratory testing.

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Marcus Palm and Carl Larsson

Wordlist

Word	**Meaning**
Hedwig	Fixed focus camera that is treated in the thesis.
ADHESIVE INSERTS	Small plastic cups
PCB ASS	PCB A and attached ADHESIVE INSERTS
OPTICS	Collective name for assembled lens, lens holder, d-n filter, d-n filter lid
OPTICAL MODULE	Collective name for assembled OPTICS and PCB ASS. with the attached ADHESIVE INSERTS
Inst ASS	Assembly instructions created by Axis for the EMS to follow
Adhesion	Force between substrate and adhesive
Cohesion	Force inside the adhesive
Wetting	The adhesives ability to spread over a surface
Curing	The transformation from liquid to solid for an adhesive

Abbreviations

Abbreviations	**Meaning**
IBAS	Image Based Alignment System
EMS	Electronic Manufacturing Services
CAD	Computer Aided Design
INST ASS.	Instructions for assembly produced by Axis and given to the EMS
PCB RAW	Printed Circuit Board without any components on
PCB A	Printed Circuit Board with components on
VSD-test	Varnish Spreading Deficiency-test
PU-test	Production Unit test where the final and complete camera is tested
PB	Photobond
OP 67	OP 67 LS
ADS	Automatic dispensing system

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1 Introduction

This chapter is to give the reader brief insight in the world of digital network cameras, Axis Communications and the production problems that exist in a modern production.

1.1 History of cameras

In our society, digital cameras are everywhere and they are used for a countless number of different purposes. Ironically enough, the first thing a person would think of when talking about cameras today is probably the one in their phone, which 20 years ago was unthinkable. There are other kinds of cameras as well such as DSLRs, point and shoot, surveillance- and action cameras. Nowadays most cameras are capable of both taking still pictures and recording video. Each type of camera is tailored for different purposes and is more or less suitable depending on the user's needs. The principle technology on which cameras are based is however the same. There are many components going in to making such a complex product but one could argue that the camera sensor and lens make out the heart of a digital camera. Essentially the lens lets light in to expose the sensor which records the light and transforms it to a digital image.

1.2 About the company

Axis Communications AB, founded in 1984, is a Swedish company which pioneered and specialize in digital network cameras. They are currently employing about 2400 employees globally with headquarters in Lund, Sweden. From the start, Axis focused on offering protocol converters, allowing PC printers to connect and communicate over IBM mainframe networks. During the emergence of the internet Axis introduced print servers and started to investigate ways to allow other types of hardware to connect over the internet. In 1996 Axis delivered the first network camera to the market and has remained a leading actor in the field ever since.

In accordance with Axis current strategy, they develop their products themselves as well as the tools and processes to manufacture the most critical parts in their products. The production is outsourced to partnering companies with whom Axis have developed close partnerships with.

1.3 Background

Regarding the development of cameras, there are various ways to achieve a focused image. In consumer products, a variety of lenses with adjustable focus are often used. In these types of cameras, the distance between sensor and lens in production is not of great of importance because the focus can be readjusted at any time. Simpler cameras use a fixed focus lens where the focus is set by a predetermined distance between the sensor and lens. As the name states, focus in this type of lens is set during production and cannot be adjusted afterwards. It is therefore imperative

that the lens and image sensor are fixed in correctly aligned positions relative to each other during production.
The thesis will focus on one of the fixed focus cameras in Axis assortment called Hedwig. In Hedwig, the lens and sensor is aligned using an internally developed system called IBAS (Image Based Alignment System). The IBAS process align the optical axis towards the image sensor, finding an optimal position where the sensor and optical axis are perpendicular. Adhesive is then used to permanently fixate the lens and sensor into desired position. In the Hedwig camera the lens is bonded to a holder, not enabling any focus adjustment after alignment have been done.

In the current process, adhesive is applied to the parts by hand using dispensing machines with high fluctuations in dispensed amount. Since the amount of adhesive and placement of the adhesive is difficult, an excessive amount of adhesive than necessary is used to compensate for the lack of control. The amount of adhesive used is controlled by weighing the parts before and after curing, eliminating the possibility for re-work as a result. The use of an excessive amount of adhesive increase cost while an insufficient amount have an effect on the product quality [1]. Shrinkage of the adhesive also affect the focus qualities due to the fixated lens. When cured, the optimal position found in IBAS is altered due to the shrinkage. As of today, IBAS compensate a fixed distance for the shrinkage based on an average amount of adhesive. Since the focus tolerance from the lens to the sensor often is less than 10 microns, the variations in adhesive have an impact on the camera. Further, the tilt between sensor and optical axis is often required to be less than 1 degree [1]. With better sensors the requirements on the tolerances increase. With a better control of the amount of adhesive dispensed, IBAS can better compensate for the shrinkage.

Axis use a fast UV-curing adhesive to be able to fully control when and how fast the adhesive cure. Adhesive is applied to the parts at the beginning of the process and cured when the desired alignment is found. However, adhesive can be challenging to work with. The curing process needs to be controlled to prohibit the adhesive from curing before the desired alignment is found. Further, the quality of the bond is dependent on a number of parameters such as quantity of adhesive, placement of the adhesive and cleanliness of the parts. The small ingoing parts makes the bonding process more difficult due to the small quantity of adhesive that needs to be placed with high accuracy.

Due to these factors, Axis Communications have expressed a need to better define and increase the reliability and repeatability of their adhesive dispensing processes during assembly of the sensor-optics module.

1.4 Problematization

In production it is always desired to find new ways to make the production process better, simpler, more repeatable and decrease amount of scrap to lower production costs. If products can be manufactured at a lower price a company can either choose to lower their selling price without losing profit margin and hopefully increase sales, or increase the profit from every product sold. In many cases, gradual price reductions are necessary to be able to compete with competitors. As a first step towards achieving a better controlled process Axis have acquired a 3-axis automated dispensing unit. The dispenser will be used to analyze the following questions:

- What is the optimal quantity of adhesive to use for each of the bonding steps?
- Which parameters needs to be controlled for a defined, repeatable and assured process?
- The adhesive used today is both expensive and toxic. Can a new adhesive, known as Photobond be successfully introduced and what effect will it have on the adhesive and the product cost?

Two types of adhesive are explored in this thesis:

DYMAX OP 67 LS (OP 67) has been used in several of Axis products over a long period of time. It is currently being used in Hedwig for three steps in the production. The adhesive performs well with somewhat stable results but comes with a few disadvantages. It is expensive, it cures in visible light which means it must be kept dark, making it more difficult to handle. It is also toxic to inhale its fumes or if in direct contact with skin. Air ventilation and gloves are thus required during usage.

DELO Photobond (PB) is an adhesive Axis are slowly introducing as a replacement for OP 67 in its products. The price is lower at 47% of the cost compared to OP 67, it is not as toxic as OP 67 and is much less sensitive to curing in visible light. It has a different viscosity and density and the wetting abilities differs from OP 67. The difference in characteristics requires it to be tested before it can be fully deployed. Brief initial tests at the manufacturer have shown Photobond to perform inferior and inconsistent compared to OP 67 with current setup and settings.

The automatic dispenser is a considerable investment if all the Electronic Manufacturing Services (EMS) suppliers in the future shall use them. Axis is interested in a method to measure the economic impact of the automated dispenser. Following questions are interesting:

- How will an introduction of an automatic dispensing unit effect the performance of the production process in each step?
- How should an automated dispensing system be used for optimal results?
- What implications will changes made to the process affect cost and quality aspects of the final product?

1.5 Aim

The aim is to investigate how to change the adhesive dispensing processes to make it more reliable, repetitive and to find ways to decrease the adhesive usage and spill. The report will give a more scientifically established view of the relationship between adhesive amount, wetting time and curing to achieve a desired bond. Further the connection between how a scientifically proven process can be transferred into large industrial use will be discussed and finished with an investigation of how these changes would influence costs and quality of the finished product.

1.6 Focus and Delimitations

The thesis study will investigate the adhesive dispensing process for Hedwig, one of the cameras sold by Axis Communications. It will focus on the different steps of the process itself as well as what consequences it has on costs and quality of the product where the sensor chip is bonded with the optics. It is restricted to the activities connected to the production of the optical module mainly performed inside the cleanroom where the dispensing and bonding process takes place.

2 Theory

This chapter works as the academic background for the reader to get and understanding the parameters that affect an adhesive bond. Relevant models which have given inspiration to how to estimate assembly cost are presented as well.

2.1 General definition of adhesive

The use of adhesive for industrial assembling dates back to the industrial revolution and is widely spread in a variety of industries and applications. For example, in the aircraft industry where the wings to the body are bonded by the use of adhesives [2] [3] [4, pp. 4-13]. The common use of adhesives is due to many factors. The ability to bond many and different materials and parts with extreme dimensions such as foil and films are characteristics that adhesive offers [4, p. 2]. Design flexibility is a factor that makes the use of adhesive popular.

An adhesive, from the word adhesion, is in general a substance that mechanically bonds two or more object together [4, p. 1]. Substances that can be used as adhesive is two part epoxy, wood glue, cement and many more [4, p. 2] [5, p. 24]. Adhesives can be described in different ways, commonly its physical form, ex. *Liquid adhesive,* chemical form, ex. *epoxy adhesive,* the use of the adhesive, ex. *light curing,* or the materials the adhesive is used for, ex. *wood glue* [4, p. 2] [5, pp. 24-35].

The adhesives in this thesis are UV-light cured adhesives that can be seen as liquid thermosetting polymer with a high density of crosslinks. When cured, polymerization hardens the polymer and locks the crosslinks in place, creating a bond between the two substrates [6] [5, p. 18]. Hence the theory will be focused on the characteristics that apply for thermosetting adhesives.

2.1.1 Wetting of a substrate

Adhesive works by bonding onto the surfaces of the substrates and when cured merging one surface to the other through the adhesive. The adhesives ability to completely cover the surface of the substrate, also called wetting, is crucial for a good bond to take place [4, p. 18] [7, p. 7]. If wetting equilibria is not achieved, the substrate and adhesive will not bond and the joining of the two substrates will not take place.

To reach wetting equilibria mainly depends on three factors; Surface tension of the substrate and adhesive, viscosity of the adhesive and surface energy of the adhesive and substrate [4, p. 18]. The parts that are bonded by the adhesives are known as substrates. There are many parameters affect how strong the adhesive bond will be. Factors such as type of substrate, surface micro structure and surface treatment have a decisive impact on the strength and service life of the bond [4, p. 18].

Wetting of a surface can be described at which angle the droplet of adhesive tangents the substrate surface [7, p. 8]. The drop that hit the surface wants to retain its spherical form due to the adhesive surface tension. The substrate that the drop hits also have a surface tension, pulling the droplet out. The interaction between these tensions define the angle between the adhesive and substrate [7, p. 8]. The angle is defined as the Young's angle (α) and is a static angle dependent on the surface tension from the three phases; liquid surface tension (γ_{LV}), substrate surface tension (γ_{SV}), and the liquid-solid interfacial tension (γ_{SL}) [4, p. 19] [7, p. 7]. The equilibria of the surface tensions are kept by Young's angle according to equation (2.1) if no absorption of the adhesive into the substrate occur and also after all the kinetic energy of the adhesive have been adsorbed [7, p. 7]. The angles and tension vectors are illustrated in Figure 2.1 [7, p. 7].

$$\gamma_{SV} = \gamma_{LV} \cdot \cos(\alpha) + \gamma_{SL} \tag{2.1}$$

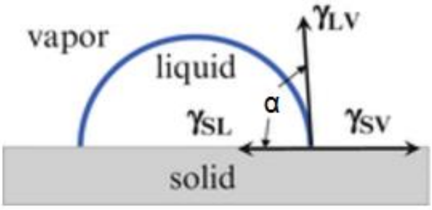
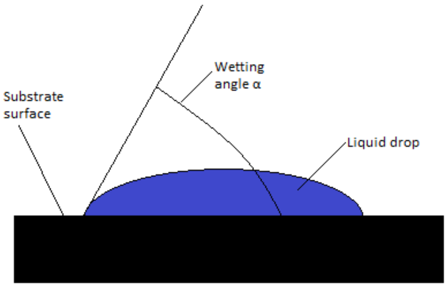


Figure 2.1. Surface tension vectors acting between a liquid and substrate [7, p. 8].

For an adhesive to completely spread over a substrate, the contact angle α is ideally zero. Of course, an adhesive can spread even though $\alpha > 0$ if an external pressure is applied affecting the equilibria [4, p. 21]. The ability to wet a surface is hence set by the choice of substrate and adhesive and independent of the viscosity if time is infinite [7, p. 9] [4, p. 21]. The relationship between the contact angle and quality of wetting is shown in Figure 2.2.



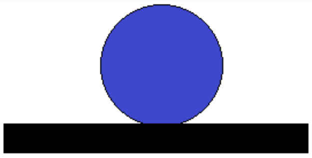
α = 0°		**Spreading**
α < 90°		**Good wetting**
α = 90°		**Insufficient wetting**
α > 90°		**Incomplete wetting**
α > 180°		**No wetting**

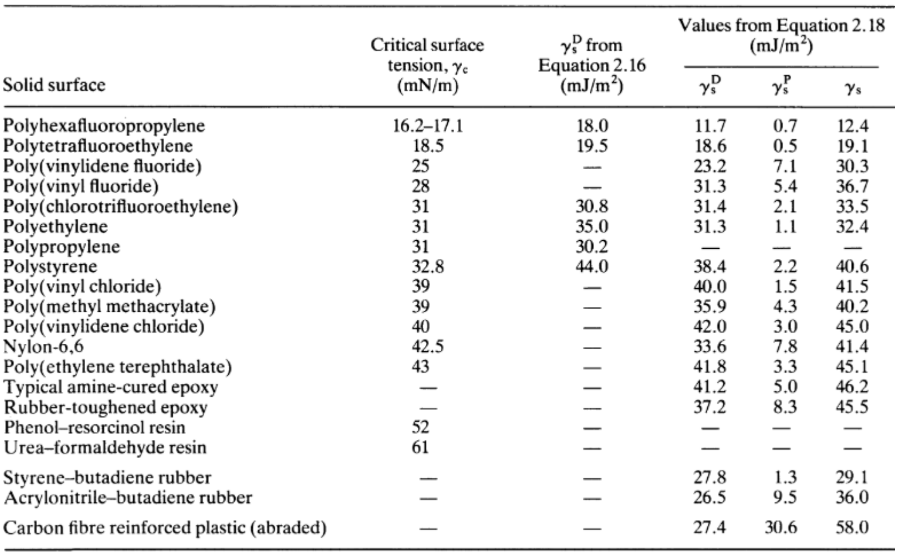
Figure 2.2. Wetting contact angle correlated to the wetting of a substrate.

2.1.2 Calculation of contact angle

An approximation of the adhesives ability to wet a substrate can thereby be calculated if the surface tension of the substrate and adhesive is known. The hard part is to calculate the interfacial tension between the adhesive and the substrate. One way to obtain this is to measure the contact angle on a drop of a known adhesive on a known substrate calculating the interfacial tension based on that [7, p. 10] [8]. The downside to this method is that the contact angle is now known and it is often the sought after parameter in industrial use of adhesive, rendering the interfacial tension to be of no use. Computer simulations can also be used to approximate the interfacial surface tension [8] [9]. The problem hampers when other surrounding conditions are taken into account, such as dirt, inhomogeneity of the substrate and adhesive chemical structure and fluctuations in temperature [4, p. 24]. These additional parameters make it difficult to assess the quality of an adhesive without physically testing and measuring the contact angle to evaluate the adhesive.

2.1.3 Low energy surfaces

Substrates are divided into two groups depending on the value of the surface tension, low energy and high energy [4, p. 24]. Low energy substrates consist of material with weaker bonds, such as Van der Waals and hydrogen bindings, while high energy surfaces have metallic, ionic and covalent bonds. Low energy surface have a surface tension below 100 mJ/m^2 and most plastics fall under this category [4, p. 24]. In the early 50's Zisman and Fox showed that there is a linear relationship between the cosine of the contact angle, the adhesives surface tension and substrates surface tension in cases when low energy surfaces were examined [10] [11]. From the experiments, Zisman and Fox stated that γ_c is the critical surface tension a substrate must have for an given adhesive to spread over the given substrate [10] [11]. The critical surface tension are often close to the surface tension for a series of polymers, as seen in Figure 2.3. However, further experiments have shown that the relationship existing is not linear but follow a curve depending on the substrate and adhesive system [12] [13]. The exact relationship is individual for every adhesive and substrate combination [13].



Solid surface	Critical surface tension, γ_c (mN/m)	γ_s^D from Equation 2.16 (mJ/m^2)	Values from Equation 2.18 (mJ/m^2)		
			γ_s^D	γ_s^P	γ_s
Polyhexafluoropropylene	16.2–17.1	18.0	11.7	0.7	12.4
Polytetrafluoroethylene	18.5	19.5	18.6	0.5	19.1
Poly(vinylidene fluoride)	25	—	23.2	7.1	30.3
Poly(vinyl fluoride)	28	—	31.3	5.4	36.7
Poly(chlorotrifluoroethylene)	31	30.8	31.4	2.1	33.5
Polyethylene	31	35.0	31.3	1.1	32.4
Polypropylene	31	30.2	—	—	—
Polystyrene	32.8	44.0	38.4	2.2	40.6
Poly(vinyl chloride)	39	—	40.0	1.5	41.5
Poly(methyl methacrylate)	39	—	35.9	4.3	40.2
Poly(vinylidene chloride)	40	—	42.0	3.0	45.0
Nylon-6,6	42.5	—	33.6	7.8	41.4
Poly(ethylene terephthalate)	43	—	41.8	3.3	45.1
Typical amine-cured epoxy	—	—	41.2	5.0	46.2
Rubber-toughened epoxy	—	—	37.2	8.3	45.5
Phenol–resorcinol resin	52	—	—	—	—
Urea–formaldehyde resin	61	—	—	—	—
Styrene–butadiene rubber	—	—	27.8	1.3	29.1
Acrylonitrile–butadiene rubber	—	—	26.5	9.5	36.0
Carbon fibre reinforced plastic (abraded)	—	—	27.4	30.6	58.0

Figure 2.3. Critical and real surface tension of several substrates [4].

From Zisman and Fox's work it have been established through tests that for an adhesive to spontaneously spread over a substrate, the critical surface tension of the adhesive must be less than that of the substrate [4, p. 38]. It is important to remember that the research above is to find the relationship between surface tensions and complete, spontaneous wetting where no external forces are applied. How external forces affect the wetting will later be discussed, but the important conclusion is that for an adhesive to sufficiently wet a substrate the surface tension of the adhesive needs to be lower than that of the substrate.

2.1.4 Influence of substrate microstructure

Substrates used in academic experiments often have known surfaces or are mathematically considered smooth. In industrial applications, the surface characteristics of an object is seldom known nor smooth. The surface roughness play an important part for an adhesives ability to completely wet the entire surface of a substrate [7, p. 55] [4, p. 41].

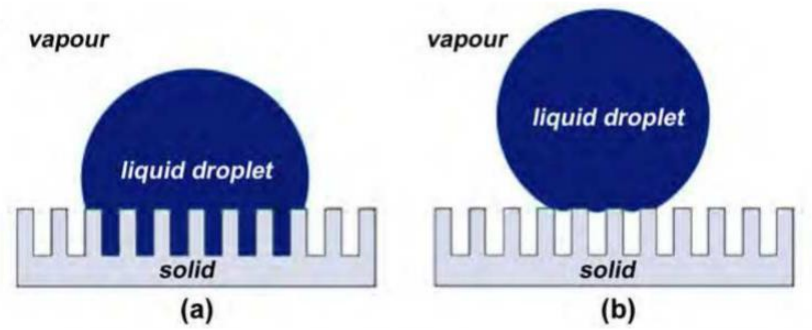


Figure 2.4. The wetting of a liquid on a rough solid surface in two states (a) Wenzel and (b) Cassies-Baxter [14].

Wetting of rough surfaces can be divided into two categories, Wenzel and Cassie-Baxter seen in Figure 2.4. [7, p. 55] [14]. As seen in the figure when Wenzel wetting occur, the adhesive in captions the abnormalities in the surface and wets the entire surface. In the Cassie-Baxter case the adhesive rests on top of the peaks trapping air bubbles in the valleys, resulting in poor wetting of the substrate [7, p. 55]. The Wenzel and Cassie-Baxter states are metastable, and can in many cases be moved, from one state to the other and also coexist by external forces, such as vibrations [4, p. 41] [15] [16].

Wenzel stated that if an adhesive wets a substrate favorably, the surface roughness will have a positive impact on the wettability of the substrate if the initial static angle is relatively low [7, p. 55] [4, p. 41] [15]. If the substrate resist wetting, the surface roughness will increase that resistance [7, p. 55] [16].

From these observations, the wetting of a substrate can be improved by vibrations and forcing the adhesive over the surface. It has not been concluded that the thermodynamics of wetting play a part in the wetting of a substrate in industrial use, since most adhesives are somehow spread over the substrate [4, p. 51]. However, the criteria that the adhesive will favorably spread over the substrate is still of importance. If the combination of adhesive and substrate does not wet well, forces, vibrations and surface roughness may result in even poorer wetting [16]. Another important aspect that is influenced by the microstructure is real area versus projected area. The microstructure increase the surface area, allowing more adhesive forces to work between the adhesive and substrate.

2.1.5 Adhesive viscosity

Adhesive viscosity is yet to be taken into account. As stated above, the ability of an adhesive to wet a substrate if time is infinite is independent of the viscosity. In most industrial applications time is of great importance and a shorter time for sufficient wetting is sought. The lower viscosity of the adhesive the shorter the time will be for the adhesive to reach wetting equilibria [4, p. 44]. The external forces that are required to wet the substrate decrease with decreasing viscosity. For the adhesives in used in the thesis, the viscosity is temperature dependent and decrease with an increase in temperature.

2.1.6 Mechanical interlocking

Up to now the importance of wetting have been discussed but not the reason why sufficient wetting of the substrate is crucial for an effective bond to take place. Adhesive forces can be separated into two categories, adhesion forces and cohesive forces [4, p. 57]. Cohesive forces are the internal forces of the adhesive while the adhesion forces are the forces acting between the substrate and adhesive. Both forces are of great importance for the final joint. If the adhesion forces are low, the substrates will not be bonded, while if the cohesive forces are low, the internal strength of the joint will be low. There is four theories why an adhesion forces take place, where mainly two are applicable when it comes to bonding of plastic, where the adsorption theory is considered to be the most likely cause of adhesion forces [4, p. 57].

The first theory to be established was that when a rough surface is properly wetted, the adhesive fill out the cavities [4, p. 57]. When cured, the adhesive is locked into the cavities and the bond is complete, as seen in Figure 2.5 a).

The theory of mechanical interlocking fails when the surface has the microstructure seen in b) where mechanical interlocking doesn't take place. Tabor with others also showed that adhesion of molecular smooth surfaces was possible when they were examining attractive forces between molecules [17] [18].

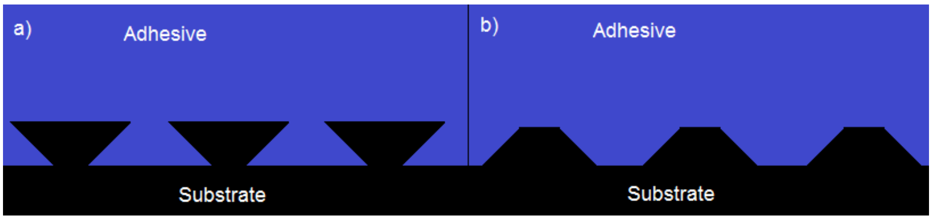


Figure 2.5. Mechanical interlocking of two surfaces. a) Interlocking of surface with negative rake angle creating mechanical interlocking. b) Surface with positive rake angle not creating mechanical interlocking.

Mechanical surface treatment, such as sand blasting and grinding seldom produce a surface structure that is suitable for mechanical interlocking [4]. The mechanical treatments rather produce surfaces that have the characteristics seen in Figure 2.5.

2.1.7 Thermodynamic Adsorption theory

The final theory and the main part of adhesion is the attractive forces from intimate molecular contact, mostly van der Waals and hydrogen bindings, but also covalent and ionic can occur [4, p. 79].

When atoms come in a certain distance the electrons and protons displace, forming an attractive force between the two atoms known as Van der Waals forces as seen in Figure 2.6. [19]. Van der Waals forces are known as secondary bonds since the bond is weaker than that of covalent and metal bonds [4, p. 79].

The interaction distance between the atoms is critical for the strength of the bond. Van der Waal interactions starts to affect the adhesive bond when the atoms are within a distance of 1 nm from each other [17] [19]. When the distance decrease, the adhesive forces increase exponentially [19]. Even though van der Waals forces are secondary forces, the theoretical calculated attractive force for two materials separated by 1 nm is 100 MPa [20].

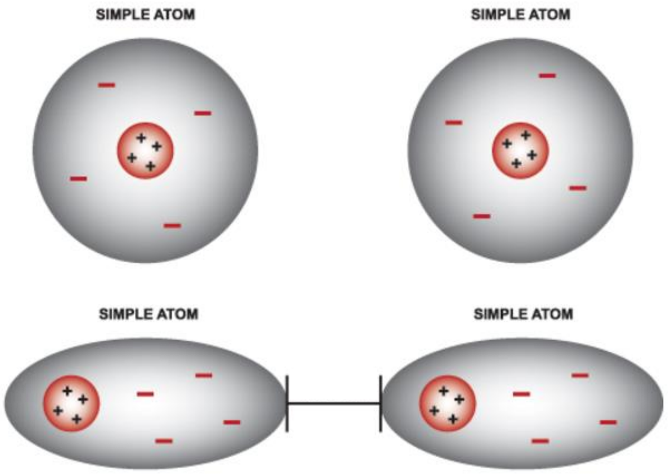


Figure 2.6. Van der Waals forces between two atoms [33].

It can thereby be argued that better wetting of a surface may increase the adhesive forces due to a larger area forms van der Waals interaction. This have also been shown in experimental studies where the surface tension of the substrate have been shown to correlate to the adhesive joint strength [4, p. 83]. Kinloch showed that there is a linear correlation where an increase in critical surface tension of the substrate resulted in an increase in measured joint strength [4, p. 83].

2.1.8 Summary about adhesive forces

Adsorption theory is considered to be the main mechanism of adhesion, but other adhesive forces such as mechanical interlocking may occur in different adhesive systems [4] [20]. Mechanical interlocking do take place in an adhesive bond, but is not the main cause of adhesion. The effect of the surface microstructure does affect the adhesive joint in the cases where the surface have a favorable micro structure [4, p. 66]. Since most surfaces doesn't have a favorable microstructure but the adhesive joint still is stronger on a rough surface the cause is likely the effect of better wetting and an increase in surface area [4, p. 66].

2.1.9 Surface requirements

For an affective adhesive bond to take place, control of the surface is commonly necessary. Grease and oils, dust and other small particles can have a decisive effect on the strength of the joint and the repeatability of the bonding process [4] [5]. If the surface is contaminated with grease or dust, the adhesive might wet and bond to contaminants covering the surface instead of the surface itself, resulting in an overall weak joint. Entrapment of air underneath irregularities in a surface will decrease the area for adhesion forces and also decrease the overall joint strength [4]. Still many plastics can be bonded without a surface treatment, particularly fiber reinforced plastics with higher surface tension [4, p. 103]. However, for a consistent joint strength to occur, the surface mostly needs to be controlled. Surface treatments that can be done to remove contaminants from the surface are many. Cleaning with water or alcohols can be done to remove most oils and particles [5]. For a better result plasma treatments can be used which also have other beneficial influences. Plasma treatments cleans the outer atomic layers, suitable for fine particles, oils and processing additives [5] [4]. Other influences are ion implantation on the surface which increasing the adhesion forces, prevent oxidation and removing weak layers on the substrate [5].

2.2 Production Development

Production development refers to the activity of changing production processes to make them more effective. It includes improvements to already existing processes and activities, or development of new production systems to increase production ability, capacity and quality [21, pp. 1-4]. J-E. Ståhl discusses four categories of parameters that are important to consider when prioritizing research and development in manufacturing. [22, pp. 22-23]:

- Quality parameters
- Down time parameters
- Production rate loss parameters
- Environmental and life cycle parameters

He argues further that these parameters at least must have a possibility to be improved to legitimize a research or development project. Increasing product requirements yields demand for increased production reliability and more integrated production processes. In many cases it calls for development of new production systems rather than increasing control of existing ones [21, pp. 1-4] [22, pp. 22-23]. Production processes and systems also need to be able to be measured from an economic stand point. Ståhl talks about an increasing interest in *Tillverkningsekonomisk Simulering (TES)* which translates to Manufacturing Cost Simulation. This type of assessment is based on a cost break down model, explained in **2.3 Cost model**. The model allows for different changes to be made and the effects to be put into an economic context in an efficient way. [22, pp. 22-23; 228-239].

2.2.1 Product manufacturing

Manufacturing is the process of converting input materials to a finished product, many times consisting of several parts and modules. J-E Ståhl categorizes different classification of units [22, pp. 29-30]:

- Components
- Modules or units made from components and input materials
- Product made from modules, components and input materials
- Similar products belonging to one product family or product group

Modules are made from several components and is a smart way of diversifying a product in several variations. Depending on the customer's needs, different modules can be used to adapt product functions for different purposes. A great example of this is the car industry where the customer in most cases have the ability to choose between customizable alternatives when ordering their car such as color, motor or interior.

Depending on type of product or commodity and its demand, different types of production systems are suitable. They are often divided into different categories based on batch sizes and product diversity [22, p. 30]. The simplest production is Single unit production which is single, or very small volumes specific to each customer order and features a high degree of customization. Air planes and busses are typical products that are produced in single unit production. The next production stage is batch manufacturing where multiple copies of the same product is produced in medium batches, often used in production to stock. After batch production the next production stage is mass production, characterized by continuous production of one product at high rate.

Manufacturing can also be divided into categories based on how products are produced in terms of production flow and layout [22, pp. 31-35]. Product oriented layout, where all process steps belonging to production of a single product are performed at the same place. This is often due to the product being very large, hard to move or requires long cycle times to complete. Another layout is functionally oriented layout. Production equipment that perform the same part of the process are located together and products are transported between. The layout allows for larger product range and increased production flexibility. Capacity sensitivity due to faulty equipment is low due to the processing steps can be rearranged if necessary. The cost of this flexibility is complex material handling with buffers in front of each work station, generating more products in production simultaneously. The last layout is line production. Equipment is lined up in a fixed processing order for a specific product, each unit transported from one station to the next without delay often using conveyors or other automatic equipment. It is characterized by short cycle times and les complex material handling but with risk of downtime for the entire line in case of failure in any the processing steps.

2.3 Cost model

There are countless models developed with the purpose of calculating costs generated in a business. Tipnis et al. divides these in to two categories for manufacturing companies [23]. Macroeconomic models consider the cost of aggregated resources utilized in an entire process while microeconomic models are focused on individual tasks and related cost driving parameters within a process.

Most companies are continuously working with production development to find and exploit new opportunities for increased efficiencies yet to be explored. But not all improvements are worth the effort. Goals and grounds to base decisions on for development initiatives need to be present. If the cost of resources required to improve a process are greater than the expected cost reduction it is better off left as it is. To help with this Jönsson et al. have developed a cost model to simulate the costs added in each processing step further looked up on in **2.3.1 Manufacturing Cost Breakdown Model** [24].

2.3.1 Manufacturing Cost Breakdown Model (MCBD)

This MCBD model is an example of a microeconomic model developed to calculate current cost of production for a part within a planning point [22]. A planning point is one or a set of automatically performed processing steps between two buffers [22]. It can also be used as a tool to simulate expected future cost of the same, based on changes to different aspects of production. MCBD focuses on costs directly related to the production process, overhead costs are not considered. It is modeled under the assumption that production is performed sequentially and within one planning point. For a part with production divided into several planning points, each planning point can be calculated separately and summed up together.

The MC model
The model divides production costs into four different categories:

- Cost of Material (k_B)
- Machine cost per hour during production (k_{CP})
- Machine cost per hour during down time (k_{CS})
- Operator cost per hour (k_D)

As discussed earlier in **2.2 Production Development** there are parameters which drives production costs and these have to be considered in an economic model to accurately calculate production costs. Rate of scraped parts (*2.2*) is the number of scraped parts during production compared to the total amount required to deliver the ordered batch. Down time rate (*2.3*) evaluates the production time compared to the nominal cycle time. Production rate loss (*2.4*) is the result of increased cycle time. It is common to reduce processing speed to combat cases where there is temporary lack of consistency in quality or to minimize down time but it results in increased cycle time.

$$q_Q = \frac{N_Q}{N} = \frac{N - N_0}{N} \tag{2.2}$$

$$q_S = \frac{t_S}{t_P} = \frac{t_P - t_0}{t_P} \tag{2.3}$$

$$q_P = \frac{t_{0v} - t_0}{t_{0v}} \tag{2.4}$$

The total manufacturing cost for one part and planning point can be calculated with equation *2.5* with the three cost parameters introduced in equation *2.2*-*2.4* as follows (Se **Appendix E** for list of symbols and their meaning):

$$\begin{aligned} k = \frac{k_B}{N_0}\left[\frac{N_0}{(1-q_Q)(1-q_B)}\right]_b &+ \frac{k_{CP}}{60N_0}\left[\frac{t_0 N_0}{(1-q_Q)(1-q_P)}\right]_{c1} \\ &+ \frac{k_{CS}}{60N_0}\left[\frac{t_0 N_0}{(1-q_Q)(1-q_P)} \cdot \frac{q_S}{(1-q_S)} + T_{SU} \right. \\ &\left. + \frac{1-U_{RP}}{U_{RP}} T_{pb}\right]_{c2} \\ &+ \frac{k_D}{60N_0}\left[\frac{t_0 N_0}{(1-q_Q)(1-q_P)(1-q_S)} + T_{SU} \right. \\ &\left. + \frac{1-U_{RB}}{U_{RB}} T_{pb}\right]_d \end{aligned} \tag{2.5}$$

2.3.2 Absorption Cost

Methods to calculate product cost, still commonly used in Sweden today, stems from EP or *“Enskilda principer för självkostnadsberäkningar”* as it is originally called. It was published 1936 in response to earlier development of the same kind in Europe and USA. Between the first and second world war, larger companies in Sweden developed more advanced calculation and division of costs in greater detail. A standardized practice was developed and recommended by SIS (Swedish Standards Institute) to be used in practice [25]. It is a method to let products absorb different costs generated by the company in order to produce them. By doing this, a total cost is assigned to each product, an extra margin for profit can be added and a final price estimated. EP consists of the categories listed below:

1. Cost of manufacturing
    a. Direct material cost
    b. Indirect material cost
    c. Direct labor cost
    d. Manufacturing overhead costs
    e. Special direct cost
2. Sales cost
3. Administrative cost

It is important to note that only costs and income related to what a company is directly offering to its customers in terms of products or services should be included in EP. Capital costs generated through investments in stock, securities or other should be kept separate. Further detail regarding what type of costs could be considered in each category above is discussed by Paulson F. and Samuelsson L. A. [25]. They also present principles when appointing costs in practice focusing on answering the five following questions:

1. What cost drivers should be taken into account for the specific calculation object? (What should be included?)
2. Where is the consumption of resources located and how should these be registered on the calculation object? (Where should it be registered?)
3. At what point should an increase in value be registered?
4. How much resources of a certain kind have been added to the calculation object?
5. How should the consumption be valued?

2.3.3 Activity-Based Costing (ABC)

Activity Based Costing was presented in the 1980's. It brought forward a new way to distribute costs in companies with a diverse and complex product mix which generated large interest at the time. In a complex company with many different types of products, it is often insufficient to solely let production volume distribute overhead costs as is the case for the absorption cost model. The greater part of resources needs to be dedicated to supporting activities such as production scheduling, machine set ups, shipments of orders, logistics activities and others in comparison to companies with few product variations and produce in greater volumes [26, pp. 81-83]. Not all incurred costs are volume related, the same activity is not always executed alike and doesn't always take the same amount of time to perform for different products [27, pp. 142-44]. ABC-analysis separates volume related from non-volume related activities such as product development and quality control when distributing costs. Direct costs are allocated to the product, overhead costs are distributed through its use of different company resources needed to support the making of the product (Figure 2.7). A proper cost driver is linked to each activity to measure the resource usage. An example would be procurement of material. The bought material can be distributed as a direct cost tied to the product while the activity itself is not dependent on the volume bought. A better cost driver would in this case be the total time spent on administrating the order. [27, pp. 46-47]

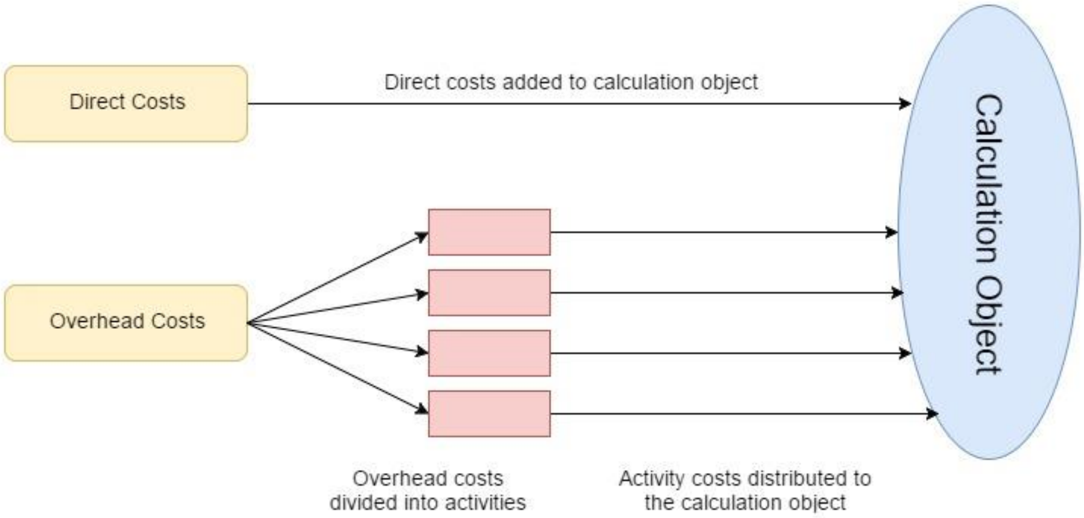


Figure 2.7. Principle illustration of cost distribution according to ABC. Direct costs such as material and direct labor are directly applied to the calculation object. All other used resources are first divided into activities linked to defined cost drivers.

Activity Based Costing is not only a tool to calculate and distribute costs. It has proven to work as basis for improvements of company activities and processes in **2.4.1 Activity Based Management (ABM).**

2.4 Quality Management

Quality management is an approach to achieve success by working with and improving qualitative aspects of company processes rather than strictly financial measurements. For manufacturing of products this means that a large degree of efforts are directed towards reducing scrap, rework, returns and waste as well as decrease defect rates and increase yields in each process step of production [26, pp. 50-51]. Over all the goal is to reduce required resources to reach desired output by taking steps towards making internal and external processes more effective.

2.4.1 Activity Based Management (ABM)

With the arrival of ABC- analysis a new type of management emerged based on the now accessible cost information. ABM consists of two dimensions - Operational (doing things right) and Strategic (doing the right things). R. S. Kaplan and R. Cooper discusses the focus in each dimension, illustrated in Figure 2.8 [26, pp. 3-6]. Operational ABM works to reduce resources needed to achieve an output. With the help of ABC-information, ABM can determine proper activities to enhance utilization of production equipment, increase efficiency through reduced down time (see equation *2.* for definition) or eliminate non-value adding activities. It gives opportunity for more stream lined processes, decreased costs and expanded capacity without the need for new investments in added equipment or recruitment of new workers. Strategic ABM uses ABC-analysis on a holistic level as a supporting tool to decide what business areas and markets to compete in.

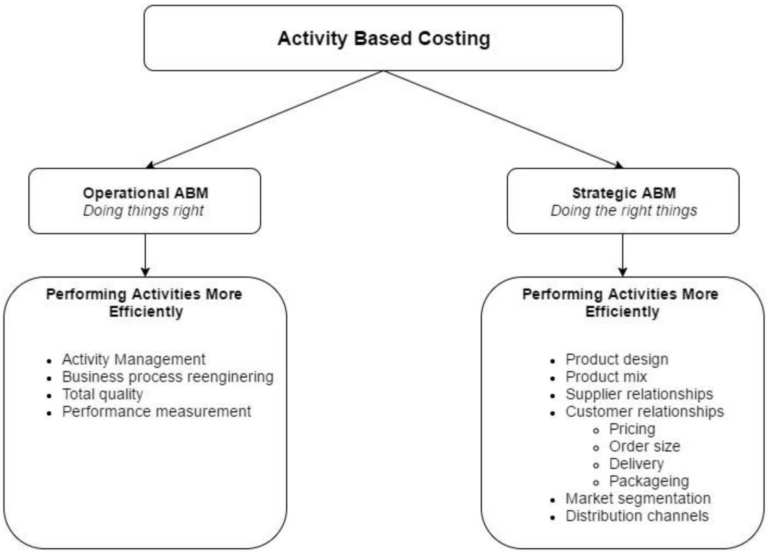


Figure 2.8. Schematic view of the two dimensions of ABM.

2.4.2 Lean Production

Lean production is a philosophy originating from Japan after the Second World War. During that time, resources were scares and needed to be used efficiently to compete on the global market. The main focus of Lean is improving the flow within and between processing steps with high level of production reliability to decrease the need for buffers and stock. Creating an environment to facilitate continuous improvement and simplicity are key to make this possible [22].

Kaizen is a philosophy within Lean. It achieves cost reduction through constant improvement of existing production processes. By finding, assessing and implementing incremental upgrades continuously, manufacturing processes can be made more efficient and decrease amount of required resources with retained output [26].

A simplified version of the Total efficiency function (*2.1*) consist of the three loss parameters q_Q, q_S, and q_P. It is intended as a tool to estimate the total efficiency of production. The lean triangle in Figure 2.7 illustrates their relative importance according to the function. Quality loss is considered in the pyramid to be the area with most impact before losses from downtime and production rate loss. This reflects well what the manufacturing industry in general have been doing in terms of dedicating resources for production and product development [22, pp. 80-82].

$$E_q = \left(1 - q_Q\right)^3 \cdot (1 - q_S)^2 \cdot (1 - q_P) \tag{2.1}$$

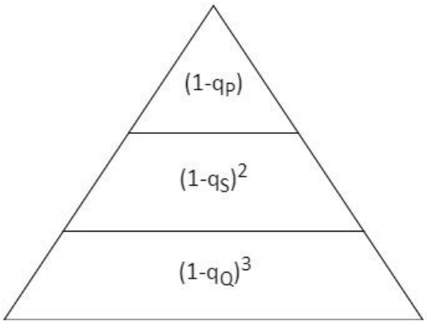


Figure 2.9. Illustration of the Lean Triangle and the prioritization hierarchy between the loss parameters according to the total efficiency function.

2.4.3 Six Sigma

Six Sigma is a production development tool introduced by Motorola in 1987 as a strategy to detect and improve upon inconsistent and defective processes by using statistical facts and methods. It is at its core a quite aggressive form of quality management. The name comes from a philosophy that the desired distribution of statistical performance data from a process should be within 6 standard deviations (six sigmas) in each direction from its mean [28] [22, pp. 306-307]. By reducing the variations in the process, the quality increase due to consistency. Six Sigma also defines process by Sigma levels, where the 6 standard deviations can be reduced to a smaller set of deviations [28]. From the sigma level and the assumption that the process is normally distributed, a theoretical yield for the process can be calculated which can be seen in Table 2.1.

Table 2.1. Theoretical yield depending on the sigma level of the process.

Sigma level	***Theoretical Yield***
1	68,27%
2	95,45%
3	99,73%

In their efforts to achieve Six Sigma for their projects Motorola also introduced DMAIC, a working method framework to find and reduce inefficiencies and variation in their processes. DMAIC is an abbreviation of the methods five steps:

- *Define* – Define the problem, what is to be achieved? Who should do what? Set a time frame for the project.
- *Measure* – Investigate the process, understand how it works and perform measurements.
- *Analyze* – Analyze results from the investigation using statistical and non-statistical methods. Determine the main factors causing the problem.
- *Improve* – Make proper changes to the process. Perform new test if needed to establish corrections or new settings.
- *Control* – Monitor the process to ensure its behavior is consistent with expected results.

This method has since been adopted by many other companies and is often compared with the concept of lean. There are similarities but the two differs in their focus. Lean works to improve the flow through and decrease waste while Six Sigma is about gaining better control over processes by decreasing variations.

3 Background

In this chapter the current process and production history is presented and analyzed to later be compared to the developed process.

3.1 Data Collection

During the time at Axis, data and information have continuously been collected through interviews, questions and production history. The production history presented in **3.5.1 Adhesive Weight** and **3.5.2 Push Out Tests**. The data have been sorted to be easier to analyze which is later discussed in **7**

Discussion.

3.2 Choice of Thesis Method

The project method chosen for the thesis study is Six Sigma - DMAIC described in **2.4.3 Six Sigma**. It was chosen due to it was developed to find and improve upon practical issues which suits this type of project well. The steps and measures taken to achieve its purpose are as follows:

Define
A broader Problematization and duration of the project was defined in conversation with representatives from Axis before the thesis was initiated and later put in to greater detail during the initial weeks of the project period. The definition of the problem is as described in **1.4**

Problematization. The main goal is to make the adhesive process more efficient, decrease the cost and attain better control while measuring its effect on cost and quality.

Measure
The investigation started with analyzing the current production to map out and learn the current process. The thesis authors visited the EMS to see and experience the full assembly process live. While on site, photos were taken, film was recorded and interviews with personal were conducted. Some observations were made and data logs were acquired to be analyzed in a later stage. Before the visit, Axis' INST ASS was gone through and several employees with insight about Hedwig were interviewed along with theoretical and financial factors.

Analyze
When the process was mapped and relevant data collected, the data was sorted, compiled and evaluated along with made observations. With good understanding of the process steps and challenges together with acquired theoretical knowledge, potential parameters and settings to focus on for further improvement were discussed and new tests could be planed.

Improve
Laboratory tests with new equipment were performed to optimize new settings and routine. Estimates of what can be expected in terms of improvements to repetitiveness, cost reduction and quality will be presented as a result of proposed changes to the process.

Control
The proposed changes must be tested and evaluated over a long period of time to ensure that results are as expected. Evaluation of the lasting effects are due to this excluded in this report.

3.3 A Three Step Assembly Process

To understand the production line, the different parts and how they fit in the process have to be introduced. The optical module in HEDWIG is comprised of eight separate parts listed in Table 3.1. All costs are presented as percentage of the total material cost.

Table 3.1. Parts going in to production of the OPTICAL MODULE.

Part	*Part number*	***Amount:***	***Part cost (%)***
ADHESIVDE INSERTS	5	4	0,7%
PCB A (Front)	7	1	40,5%
LENS	1	1	31,5%
LENS HOLDER	6	1	0,7%

DAY-NIGHT FILTER	4	1	19,1%
DAY-NIGHT FILTER LID	3	1	0,4%
SENSOR GASKET	2	1	0,7%
ADHESIVE – OP 67		**~0,217 g**	**6,4%**

All process steps are broadly described below. For a brief step by step guide compiled from INST ASS see **Appendix A.** In Figure 3.1, an exploded view of the OPTICAL MODULE can be seen. For part name correlated the numbers to Table 3.1.

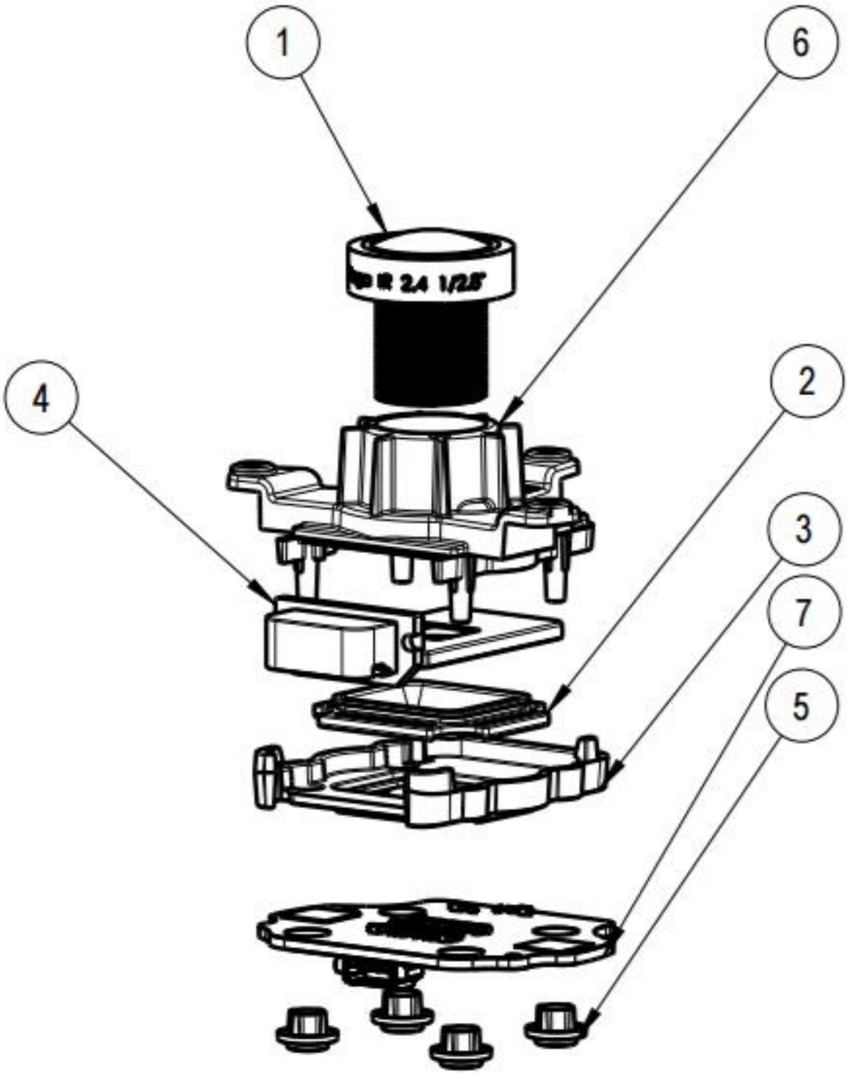


Figure 3.1. Exploded view over the OPTICAL MODULE. Part description is explained in Table 3.1.

STEP 1 – PCB ASS:
Four ADHESIVE INSERTS, referred to as cups in the flowchart (Figure 3.6)) are bonded to the PCB A. Adhesive is first dispensed manually to the flanges of the cups before the PCB A is pressed on top in a fixture as can be seen in Figure 3.2. A cylinder is used on each cup to apply extra force and thus increase the wetting. The fixture is then put under UV-light to cure the adhesive. The ADHESIVE INSERTS are now bonded to the PCB A generating a PCB ASS unit.

Figure 3.2. LEFT - Adhesive is applied to the ADHESIVE INSERTS. RIGHT - PCB A is placed on top of the inserts in the fixture.

STEP 2 – OPTICS:
LENS and LENS HOLDER are put in a fixture. Adhesive is dispensed in two cavities between holder and lens explained in Figure 3.4. The fixture containing the two parts and the applied adhesive is placed under UV-light to cure. When the adhesive is cured the DAY-NIGHT FILTER, which aids the cameras low light capabilities, is put in to place in the LENS HOLDER over the LENS as seen in Figure 3.3. The cover, called DAY-NIGHT FILTER LID, with the SENSOR GASKET pre-attached is snapped in to place to secure the D-N FILTER. This assembly is referred to as the OPTICS.

Figure 3.3. TOP LEFT – D-N FILTER is placed in the LENS HOLDER. TOP RIGHT – D-N FILTER LID with SENSOR GASKET. BOTTOM – D-N FILTER LID is snapped in to place over the D-N FILTER.

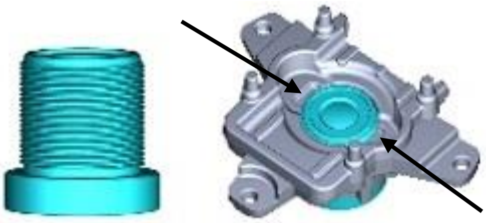


Figure 3.4. LENS and LENS HOLDER Assembly. The cavities for adhesive application are highlighted by the yellow arrows.

STEP 3 – OPTICAL MODULE:

In the final step the OPTICS and PCB ASS are bonded together by first dispensing adhesive into each cup on the PCB ASS, se Figure 3.5. The PCB ASS is later inserted with the OPTICS into the IBAS. The pins on the LENS HOLDER, see Figure 3.4, are fitted and aligned in the cups during the IBAS process. When the positioning of the two parts is found for correct focus the adhesive is cured. The OPTICAL MODULE is now complete. To make sure that the adhesive is completely cured, the OTICAL MODULE is placed in an UV-oven for 30 seconds after completion in IBAS.

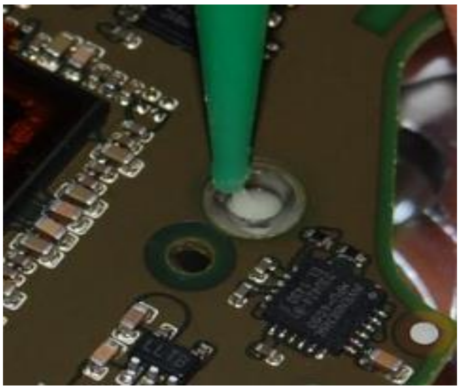


Figure 3.5. Adhesive is applied in the ADHESIVE INSERTS on the PCB

3.4 Overview Production Flow

An overview of the current process is shown in Figure 3.6 where the activities and production line are explained. Preparation of the PCB ASS and OPTICS can be done concurrently while the bonding of the OPTICAL MODULE can't be done until both the PCB ASS and OPTICS are finished. The production steps are set by Axis with input from the EMS and a rough sketch of the line is done by Axis. When the final design of the product is set, the EMS is responsible for building the main parts of the assembly line, including fixtures. For critical segments in the process, such as the IBAS process, Axis design, build and maintain the production line, while the EMS only use it for production. The production planning is solely done by the EMS, and balancing, batch or single production is decided by the EMS. The production for the optical module follow a functional layout.

The flowchart also shows what types of activities that take place throughout the production line. The total number of activities to assemble an OPTICAL MODUL is 28. Ten of these are considered to be non-value adding since they are done only to ensure that the process is done correctly. Red boxes are activities that lack or partially lack control or consistency in amount or position of the dispensed adhesive. These activities also lead to the non-value adding activities, and make them necessary. White boxes are either activities that add value by assembling or supporting activities needed to be able to assemble the product. Blue boxes are the main process taking place where the parts are bonded. Cycle times for each of the steps are presented in Table 3.2.

Table 3.2. Cycle time for each individual step.

Step	***Cycle time (s)***
1	82
2	108
3	290

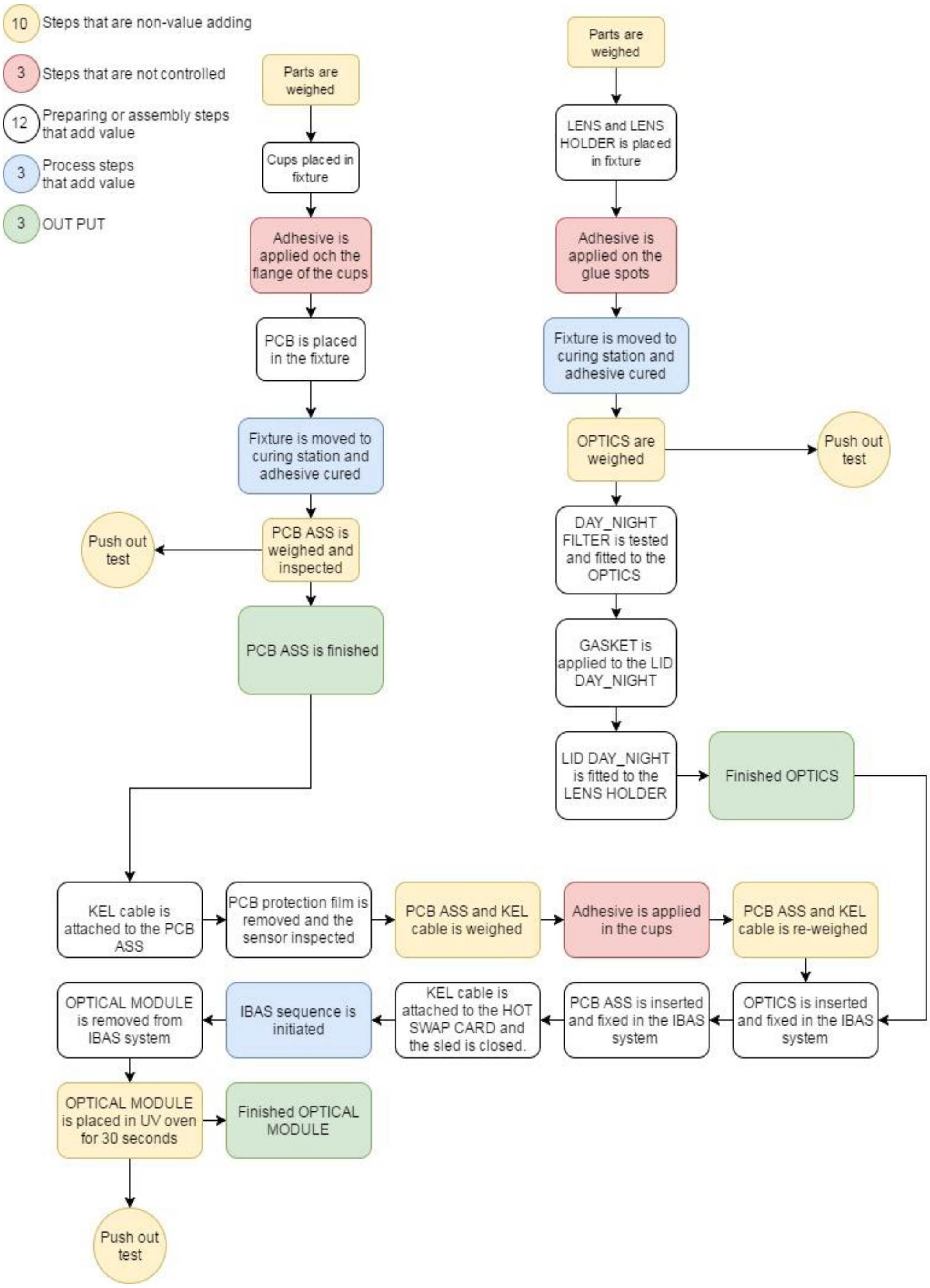


Figure 3.6. Flowchart of the current process.

3.5 Quality Control

In each step described in **3.3 A Three Step Assembly Process** the assembly is tested for correct adhesive amount and push out tests are performed. The PCB ASS has an attached barcode which is scanned in every step before commencing any activity. The computer tells the operator if the previous step has been accepted and approved for further processing. The OPTICS built in STEP 2 however does not have a barcode.

3.5.1 Adhesive Weight

For every new unit, parts are weighed before and after adhesive has been applied. In STEP 1 and 2 reweighing takes place after the adhesive has been cured for practical reasons. In STEP 3 the reweighing is done before the PCB ASS is placed in IBAS together with the OPTICS. Each of the processing steps have a defined weight interval listed in

Table 3.3. Scales are connected to computers which logs the difference as adhesive weight and checks if it is within the interval. If the measured adhesive weight is outside the specified interval the part is not approved and either reworked or scraped. Rework is only commenced to recover LENS and DAY-NIGHTFILTER. DAY-NIGHT FILTER LID is also recovered when possible. The characteristics of the adhesive bond between the LENS and the LENS HOLDER makes it possible to recover the LENS from the holder by applying twisting force to the LENS. All other parts are scraped.

Figure 3.7. Example from STEP 1: LEFT - Parts are weighed before adhesive application. RIGHT – Parts are reweighed after the adhesive is applied and cured.

Table 3.3. Acceptable adhesive weight interval in each step according to specification.

Process Step	***Accepted Adhesive Interval (mg)***		
	min	nominal	max
Step 1	64	80	96
Step 2	30	40	50
Step 3	80	100	120
Total	**174**	**220**	**266**

3.5.2 Push Out Tests

Push out tests are performed at the start of every shift, after every break and on 1% of assembled units in all three steps. The test is to find out how much force the adhesive bond between parts can withstand before it breaks. By this value, the process can be validated, meaning that the curing, dispensing and wetting are correct. In STEP 1, push force is applied to the ADHESIVE INSERTS, in STEP 2 it is put on the lens top part vertically without D-N FILTER or D-N FILTER LID assembled on top (se arrows in Figure 3.4), in STEP 3 the force is put on the sensor to push the pins out of the ADHESIVE INSERTS, the LENS and D-N FILTER are removed beforehand.

Figure 3.8. The push out equipment. The metal arm pushes down on marked spots on the fixture which transfers the force on to the desired location on the unit.

Axis have established critical values which the push-out forces are evaluated by. When the cups are pushed out with a force less than 130 N, the process is looked over but no further actions are taken. If the push-out value is less than 100 N, one more unit is produced and tested. If that unit also fails the push-out test, the previous 99 units produced are put in quarantine while Axis together with the EMS decide how to resolve the issue for the remaining 99 units. In most cases all the parts are scrapped since it is not known what is causing the low push-out forces [29].

3.5.3 Rejects

Rejects are generated when the adhesive weight control fails or if products are quarantined after multiple failed push out test. In reality, not all quarantined products are scraped. But the amount of resources needed to analyze and rework while halting production is for simplicity in this thesis considered to be equivalent to the cost of scraping. The calculated yield in each step from these two factors is not used by either the EMS or Axis as it is today. Rejects are instead linked to the optical module in the final PU-test through error codes of which focus, blemish and D-N-FILTER are common examples for Hedwig. The yield regarding the alignment in IBAS is not taken into account in the thesis. The fail in IBAS is due to faulty parts and can hence not be related to the adhesive.

3.6 Process Control

From previous work at Axis, a risk evaluation has been made to see what parameters and how the parameters affect the adhesive joint. The data have been summarized and is presented with the author's observations in Table 3.4. What influence wetting, form of the adhesive string, and precision have on the bond have not yet been analyzed by Axis. Either knowledge or the ability to control the process have led to that these parameters have been left out of the risk evaluation.

Table 3.4. What parameters that affect the adhesive joint in step 1, how the parameters affect the joint and how hard they are to control.

What parameter affect the joint	**Is the parameter controlled today**	**How hard is it to control the parameter (1-3)**	**Impact on the process (1-3)**
Operator	Partly	Somewhat difficult	3
Dispenser tolerance	Partly	Easy	2
Quantity of adhesive	Operator and dispenser dependent	Somewhat difficult	Unclear
Precision of the adhesive bond	Operator dependent	Difficult	3
Product design for correct adhesive bond	Partly	Easy	3
Cleanliness of the Parts	Partly	Easy	3
Surface structure of the materials	No	Difficult	1
Adhesive system	Partly	Easy	2
Curing time	Yes	Easy	Unclear
Curing intensity	Yes	Easy	Unclear
Wetting	No	Easy	Unclear

3.7 Manufacturing Cost Parameters

Axis does not currently have a structured record of how much the OPTICAL MODULE constitutes to the total product cost or how it is divided over the process steps. The EMS have calculated the value for finished PCB ASS, OPTICS and OPTICAL UNITS. However, the calculations are not transparent enough to tell where the costs arise, and are hence only used as base for push out cost calculations and guidance in the thesis.

Axis sources Hedwig cameras at a fixed price per unit, agreed up on during negotiations with the EMS. Because of their close partnership and level of integration, some economic parameters have been found. With the step by step approach presented in section **2.3.2 Absorption Cost** as a guideline cost driver in the production were found.

Axis have negotiated a 98% yield for Hedwig. The yield is not met in practice and most of the increased cost from rejects is today absorbed by Axis. No yield is logged in any of the processing steps but the weight data analysis in **3.8.1**Adhesive Weight **Adhesive Weight** serves as grounds for yield measurements along with scraped parts from quarantined units after test fails in Push out later explained in **3.8.2 Push Out-Tests data analysis.**

Because the focus in this thesis revolves around adhesive consumption and the assembly process, only resources connected to the process steps are considered. Axis has little insight as to how overhead costs are distributed on the product as they do not own the production. Consequently, the cost estimate concerns mainly the direct costs. Observed consumption of resources is therefore located at the manufacturer. How the different cost parameters are applied on each unit is described in **3.7.1 Cost Break Down**.

3.7.1 Cost Break Down

The cost calculation is divided into two parts. The first part is to translate and quantify known process parameters and estimate the current cost of an optical unit. The second part is to use the same model to insert parameters for the new process which is done later in chapter **6**

Analysis**.** The cost break down takes inspiration from the MCBD-model described in **2.3.1 Manufacturing Cost Breakdown Model (MCBD).**

Production cost estimate for the OPTICAL MODULE is broken down into categories, the same calculations have been made for all three steps of the process. The final OPTICAL MODULE is completed in STEP 3 and consists of the final parts assembled in STEP 1 & 2. The cost of material in STEP 3 is the therefore the sum of total cost for the two previous processing steps. Total cost for STEP 3 is the total cost for the final OPTICAL MODULE. Equation 3.1 was used to calculate the unit cost for each step in the production.

$$\frac{(k_b + k_{ba} + k_d \cdot t_0 + k_c)}{\left(1 - Q_{qa}\right) \cdot \left(1 - Q_{qp}\right)} + C_p \cdot t_f \tag{3.1}$$

Material Cost k_b

Axis own the contracts with suppliers delivering strategic parts including sensors, filters, preassembled modules and others. Standard components such as screws, cables, resistors and capacitors are specified by Axis but contracts are managed by the EMSs themselves. Axis have knowledge of the markup price for these components but the final price negotiated with second tier suppliers by the EMS may differ.

Material cost k_b is the cost of parts before any processing have been commenced. Original part value has been increased with 5% to account for handling cost upon recommendation from Axis [30].

Adhesive Cost k_{ba}

Adhesive is also a material but is separated as this is the main focus in this report. This cost category constitutes of several sub categories and calculated with equation 3.2:

C_a	Adhesive cost per gram
A_A	Average applied amount adhesive in process step
Q_{use}	Amount adhesive used in tube before discarded
L_A	Estimated leakage during cycle time (mg/s)

Spill is calculated by multiplying the cycle time in each process step with the rate of leakage. The spill was measured to 0,1 mg/s at the EMS. Total adhesive cost is divided with an estimated percentage to account for adhesive left in the tube after it is discarded.

$$k_{ba} = \frac{C_a(A_A + L_A \cdot t_0)}{Q_{use}} \tag{3.2}$$

Operator Cost k_d

The true hourly cost per operator used by the EMS when calculating quotations is not known but Axis have a rough estimate of what it should be [31]. Along with observations made during the visit on sight regarding cycle time, listed in in Table 3.2, operator cost for each of the three production steps can be calculated.

Calculated based on cycle time in each step. Cycle time, t_0 is measured in seconds. Operators are assumed to average 80% active time during a working day which can be viewed as a down time rate or production rate loss of 20%. Any extra time left after completing tasks for Hedwig is assumed to be spent on tasks related to other camera models.

Push Out Test Cost

Axis is charged a fixed amount per delivered camera. The formal instruction says to perform tests at beginning of every shift, after every rest and on 1% of all assembled units in each processing step but every time the test gives unsatisfying results it is repeated on a new unit. The push out cost is the EMS calculated cost for a tested unit multiplied by the test frequency (t_f) for that step.

In the push-out history sourced from the manufacturer the total number of weighed units and pushed out units can be calculated for each day. By dividing the number of pushed out units by weighed units, the true push out frequencies were obtained. Two versions of the Push out test cost have been calculated with the invoiced frequencies and the true frequencies

Machine cost k_{cs} and k_{cp}

IBAS is developed by Axis and lent out to the EMS free of charge. The existing costs related to IBAS including cost of energy usage and floor space is applied as an overhead cost by the EMS [32]. Investment cost for IBAS, carried by each optical module have previously been estimated through brief calculation by one of Axis employees [31]. This carried cost is used as k_{cs} and k_{cp} in the Thesis. It is an internal cost at Axis and is therefore not part of the costs paid to the EMS.

Equipment currently used in the process such as manual adhesive dispensers, scales and computers are too inexpensive to have meaningful impact on the total unit cost. The push out test cost is known and added as a test cost, hence the push out machines are thus not included in the machine cost. When calculating costs for the new process, the machine cost per unit for the automatic dispenser will be added to the machine cost.

Yield Cost Q_{qa} and Q_{qp}

Yield in each step is calculated based on the adhesive weight test performed in each step together with quarantined units from failed push out tests. Yield from adhesive tests ($Q_{qa)}$ is presented in **3.8.1 Adhesive weight data analysis**. Yield caused by quarantined units from Push out tests ($Q_{qp)}$ are presented in **3.8.2 Push Out-Tests data analysis.** Yield from the two sources of rejects are multiplied with each other. The total cost (Push out test excluded) is divided by the yield to account for scrapped units. Yield is not based on the rejects from PU-tests because the error codes does not describe the source of the error.

3.8 Analysis of Current State

Collected data and observations made during the pre-studies are presented after the data have been sorted and consolidated. The unit cost is calculated using the model derived in **3.7.1 Cost Break Down.**

3.8.1 Adhesive weight data analysis

Data logs supplied by the manufacturer, containing adhesive weight dispensed in each process step, demonstrates a normal distribution behavior. The results are illustrated in Figure 3.9-Figure 3.11 and Table 3.5-

Table 3.7. Important to note is, as can be seen in the tables, that the allowed weight interval specified in INST ASS. are set with 20% gap over and under the desired amount, in STEP 2 it is 25%. This is to account for variations in the dispensers. In STEP 1 and 2 the allowed weight intervals seem to have been altered. The data collected from these steps show expected distributions but around a different average than what is specified. In their respective tables, it is presented as *Used Limits* while *Limit INST. ASS.* is the interval specified by Axis in INST ASS. Yield in each process step is calculated with the respective limits applied to the same data set in all three steps. It is calculated as the number of parts within the limits in relation to the total number of measured parts. For calculation of costs in the cost break down, section **3.7.1 Cost Break Down**, the yield related to *Used Limits* is used. It gives the most accurate results since these limits are used at the manufacturer to determine pass or fail in the adhesive weight test described in **3.5.1 Adhesive Weight.**

In STEP 1 the distribution is offset 14 mg too low compared to what is specified in INST ASS at 66 instead of 80 mg (see Table 3.5). Since there are no specified requirements on yield for correct adhesive weight, as this statistic is not used today, there is nothing to compare it to.

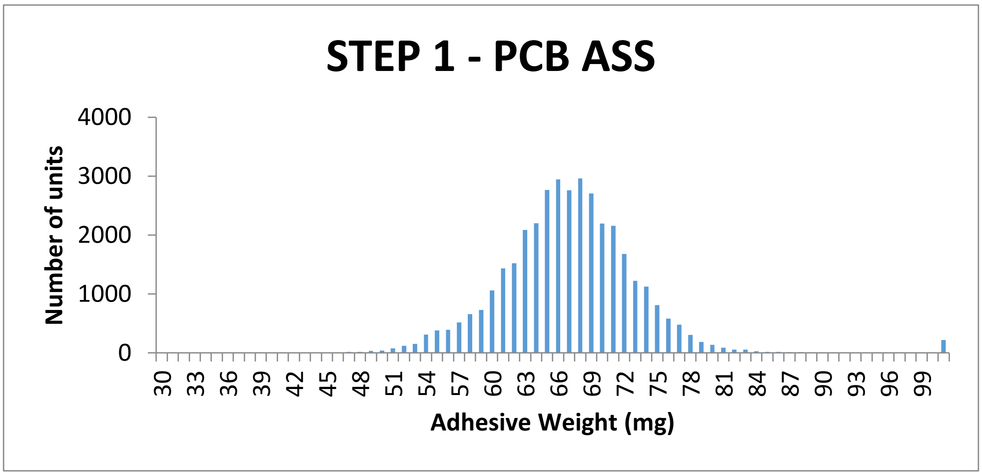


Figure 3.9. Distribution of adhesive weight from dispensing in STEP 1 - PCB ASS.

Table 3.5. Adhesive weight distribution data STEP 1 – PCB ASS.

Parameter	***Value***	***Unit***	***Yield:***
Mean	66,0	mg	
STD	6,6	mg	
5% - percentile	56,1	mg	
95% - percentile	75,2	mg	

Interval Inst. Ass.	64-96	mg	47,5%
Used Interval	50-80	mg	98,2%
Cycle Time	82	s	

Weight distribution in STEP 2, shown in Figure 3.10, is also offset. The mean is 10 mg to high at 50 mg instead of 40 mg as shown in

Table 3.6. As for STEP 1, *Used Limits* are used to measure yield in the cost break down for STEP 2.

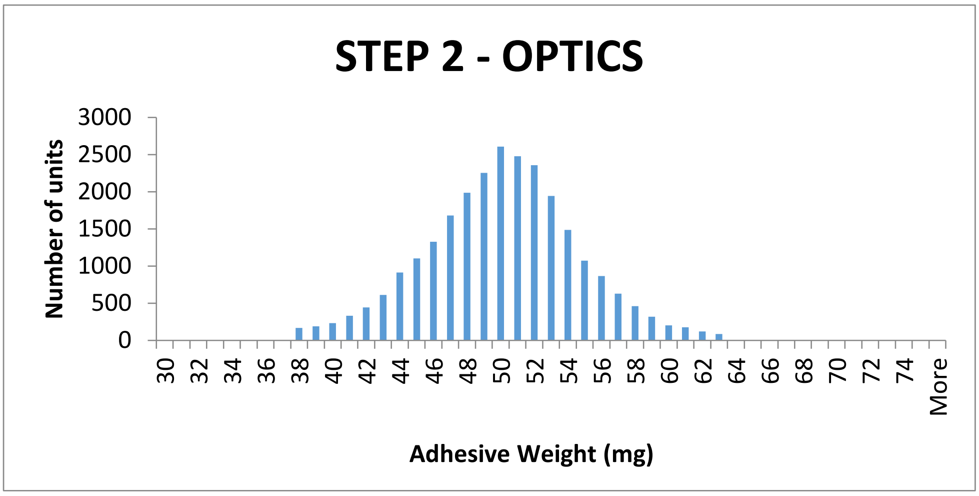


Figure 3.10. Distribution of adhesive weight from dispensing in STEP 2 – OPTICS.

Table 3.6. Adhesive weight distribution data from STEP 2 – OPTICS.

Parameter	*Value*	*Unit*	*Yield*
Mean	49,6	mg	
STD	4,5	mg	
5% - percentile	41,9	mg	
95% - percentile	57,2	mg	
Interval, Inst. Ass.	30-50	mg	52,10%
Used Interval	40-60	mg	96,20%
Dispensing Time	42	s	
Cycle Time	108	s	

In STEP 3 the results from Figure 3.11 and

Table 3.7 indicate that the same limits are used at manufacturer as in INST. ASS. According to data logs, all weight tests performed in this step have been within the allowed interval with 100% yield.

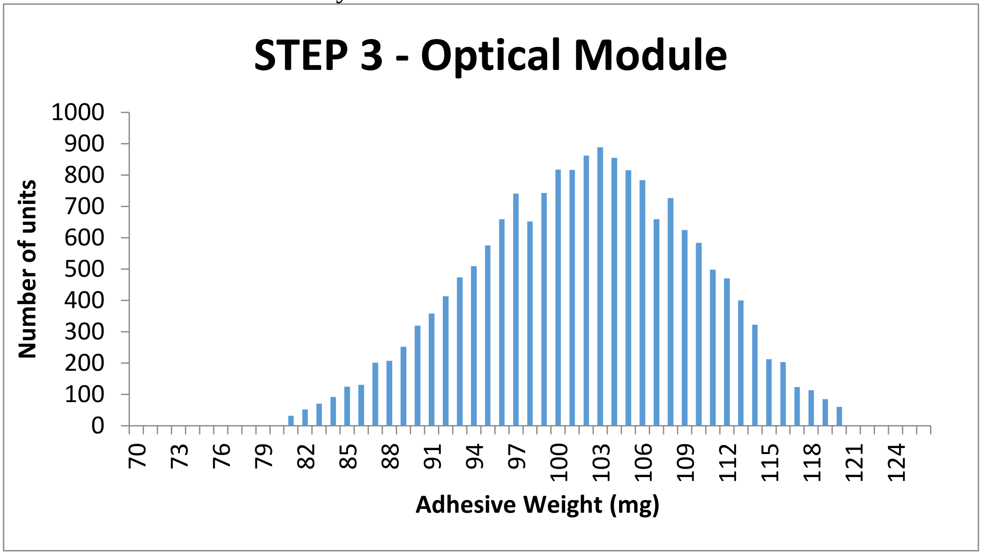


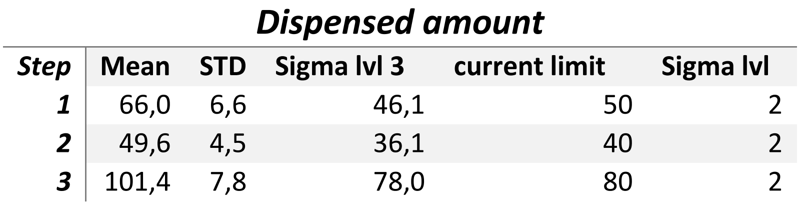
Figure 3.11. Distribution of adhesive weight from dispensing in STEP 3 – OPTICAL MODULE.

Table 3.7. Adhesive weight distribution data from STEP 3 – OPTICAL MODULE.

Parameter	*Value*	*Unit*	*Yield*
Mean	101,4	mg	
STD	7,8	mg	
5% - percentile	87,9	mg	
95% - percentile	113,8	mg	
Interval, Inst. Ass.	80-120	mg	100%
Used Interval	80-120	mg	100%
Dispensing Time	40	s	
Cycle Time	290	s	

Applying the Six Sigma methodology, sigma levels for all three parts of dispensing can be calculated. The histograms show normally distributed process for all three steps. The sigma levels are presented in Table 3.8. For all three steps the sigma level is 2, but STEP 3 is very close to being sigma level 3.

Table 3.8. Six Sigma analysis for the disnepsing at the EMS.



Dispensed amount

Step	Mean	STD	Sigma lvl 3	current limit	Sigma lvl
1	66,0	6,6	46,1	50	2
2	49,6	4,5	36,1	40	2
3	101,4	7,8	78,0	80	2

3.8.2 Push Out-Tests data analysis

The variation in push-out force for step 1 is high which can be seen in Figure 3.12 but majority of the values are over the limit. Table 3.9 show the statistical parameters for the distribution. For future comparison, later discussed in **0**

Improvement process, the push out values were modified and the new parameters are presented in Table 3.10. By modified means that all push-out forces exceeding 190 N were set to 190 N. If one of the four cups on a PCB fails the test, the whole PCB fail and is scrapped.

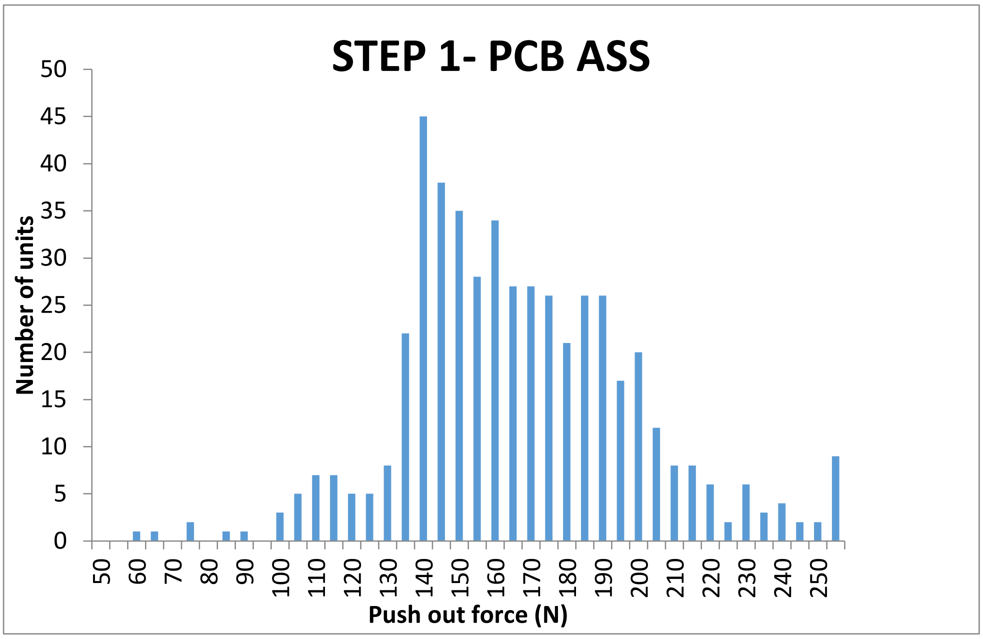


Figure 3.12 Distribution of push-out forces for STEP 1 cups pushed from PCB A.

Table 3.9 Statistical parameters for the push-out forces for STEP 1. The distribution can be seen in Figure 3.12.

	Value	***Unit***
mean	164,47	N
STD	34,14	N
5% -percentile	113,34	N
Warning limit	130	N
Critical limit	100	N
Actual test frequency	1,7	%
Yield	97,15	%

Table 3.10. Modified data where all forces exceeding 190 N are set to 190 N.

	Value	***Unit***
mean	159,66	N
STD	25,70	N

5%- percentile	113,28 N

Figure 3.13 shows no clear pattern that all cups on one PCB ASS are bonded equally. Sometimes all the cups need similar force to break the bond while on other PCB ASS it can differ more than 200 % between the lowest and highest recorded force. From the Push-out history, sourced from the manufacturer, the yield was calculated. The data show that 2,85% of the test generate the result that production should be stopped and produced units put in quarantine.

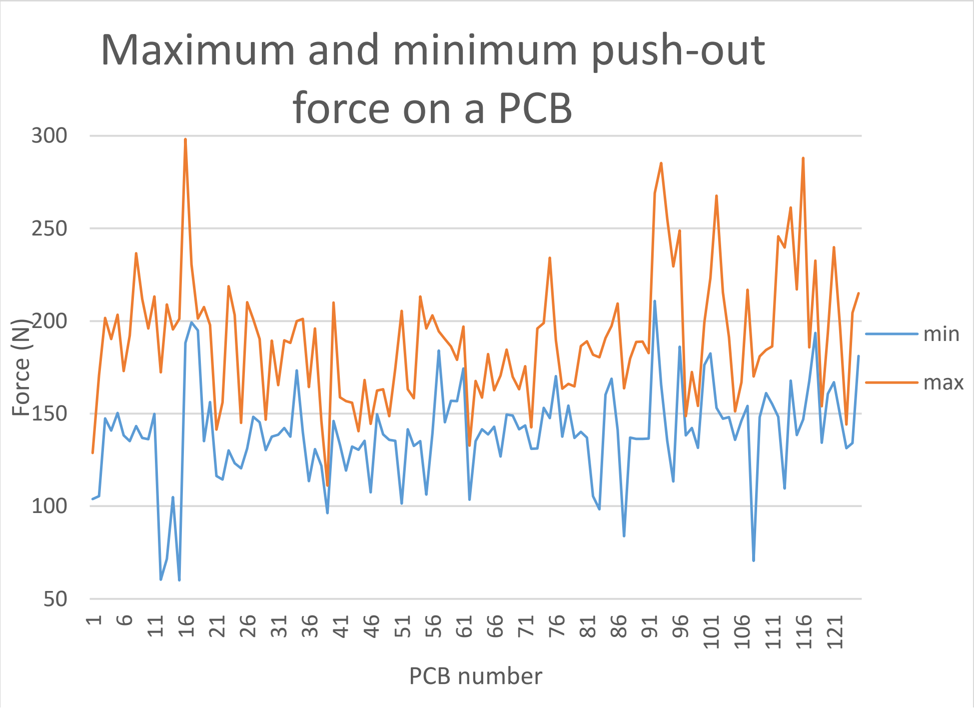


Figure 3.13. Variations of the push-out forces on a single PCB ASS.

Push-out forces for the OPTICS in STEP 2 is randomly spread with a slight indication of a normal distribution around 275 N seen in Figure 3.14 and Table 3.11. The distribution is however very flat where 90 % of the values are within an interval of 150 N. Out of all the tests performed at the EMS, no units have failed according to the data logs.

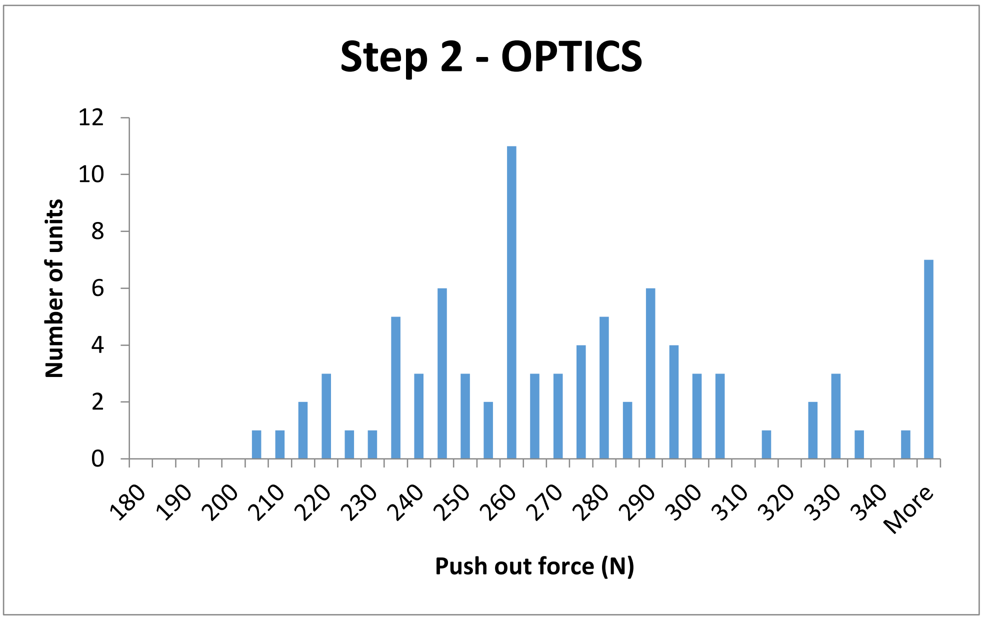


Figure 3.14. Distribution of push-out forces for STEP 2 – LENS pushed out from the LENS HOLDER.

Table 3.11. Statistical parameters for the push-out forces for STEP 2. The distribution can be seen in Figure 3.14.

	Value	***Unit***
Mean	276,46	N
STD	46,61	N
5% -percentile	215,69	N
Warning limit	210	N
Critical limit	170	N
Actual test frequency	1,8	%
Yield	100	%

The push-out forces presented in Figure 3.15 and Table 3.12 of STEP 3 shows a stable process with high push-out values and low standard deviations. However, there are other important aspects related to the bonding in STEP 3, later explained in **0**

Method**, Optimal Amount of adhesive to use**. Out of all tests performed at the EMS, no units have failed.

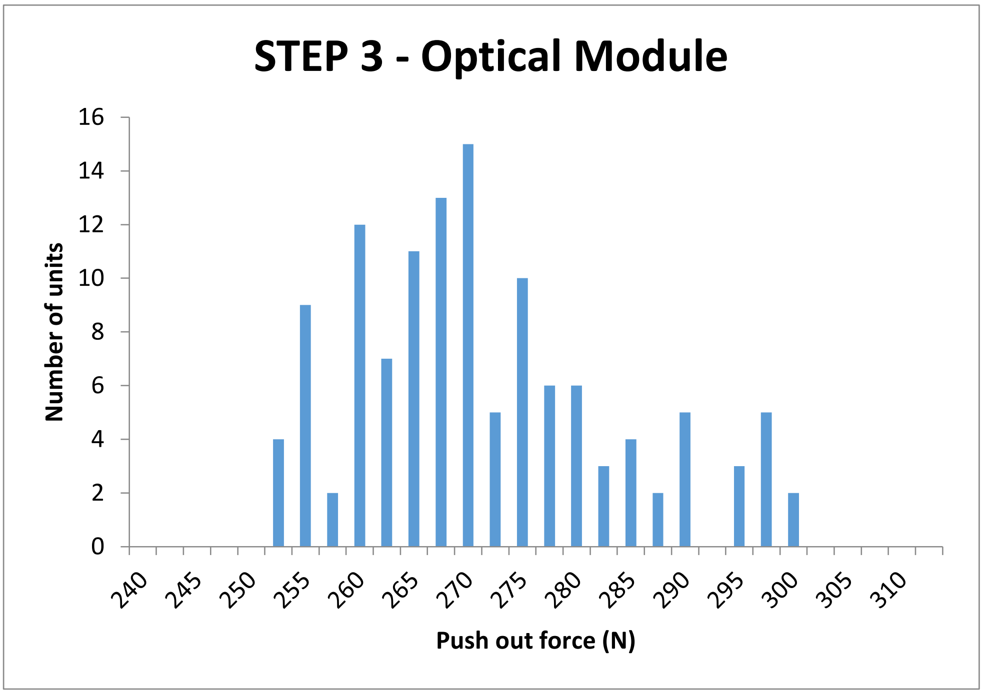


Figure 3.15. Distribution of push-out forces for STEP 3 – PCB ASS pushed out from the OPTICS.

Table 3.12. Statistical parameters for the push-out forces for STEP 3. The distribution can be seen in Figure 3.15.

	Value	***Unit***
Mean	270,32	N
STD	12,00	N
5% -percentile	253,66	N
Warning limit	250	N
Critical limit	200	N
Actual test frequency	1,0	%
Yield	100	%

In the current process Step 1 and 2 reach a sigma level of 2, while step 3 reach a sigma level of 6. Regarding the push out forces for step 3, the process can be considered extremely stable, while step 1 and 2 have some variations with a theoretical yield of 95,3 %.

Table 3.13. 6 Sigma analysis and sigma levels for the push out forces measured at the EMS over the past months.

Push Out Forces

Step	Mean	STD	Sigma lvl 3	current limit	Sigma lvl
1	159,7	25,7	108,3	100	2
2	276,5	46,6	183,2	170	2
3	270,3	12,0	246,3	200	6

3.8.3 Cost Analysis

After breaking down the three processing steps and related costs, several things could be concluded. As seen in Table 3.14, parts going in to assembling an optical module comprise the largest part of the total cost, which is natural. The lens, PCB A and D-N FILTER are expensive parts and as the operator cost show, the process is not financially labor intensive despite having manual steps involved in the process. The OPTICAL MODULE make up roughly 30% of the cameras cost.

Table 3.14. Short overview of the cost brake down sorted in each cost category for the OPTICAL MODULE. All costs are presented as percentage of the total cost for the module.

Category:	*Cost (per unit):*
Material (k_b)	79,10%
Adhesive cost (k_{ba})	5,40%
Operator (k_d)	3,60%
Push-out test	6,80%
k_{cs} and k_{cp}	***1,30%***
Yield Cost	3,80%
OPTICAL MODULE	100%

Adhesive-, operator- and push out-cost should be the three areas of interest. The fixed push out test cost per unit is greater than the estimated adhesive cost. As displayed in the results, the EMS base their cost calculation for push out tests on test frequencies that differs from what have been discovered to be the true frequency. Their calculations are based on predicted values instead of historic data which explains the difference. With access to real test data it would be more accurate to use the real frequencies. Late in the investigation of the push out test cost it was discovered that the required test frequency in STEP 2 have been lowered to 0,5%, before the latest push out-cost calculation was presented by the EMS. The EMS still calculates its cost based on the old requirement 1%, which shows that there is a gap in the information chain.

Adhesive usage currently average around 5,4% of the total value of the module. The currently allowed amount-interval in each step permits it to be manually dispensed but the accuracy of the dispenser is hard to guarantee. Excessive adhesive usage which is needed today to compensate for inaccuracy in the process adds unnecessary cost. Adhesive leakage from the tubes is hard to reduce with the current manual dispensing process where the units are produced one at a time. Leakage occurs every time the tube is set down between dispensing. When comparing the specified interval from Inst Ass in Table 3.15 to the used interval determined in **3.8.1 Adhesive weight data analysis** and presented in Table 3.15. It is evident that while intervals have changed in the separate steps, the total adhesive amount and financial impact on the product has not changed significantly as seen in Table 3.16.

Table 3.15. Cost allocation with adhesive interval specified in Inst Ass.

	Adhesive usage (mg)				
	STEP 1	**STEP 2**	**STEP 3**	**Total amount**	**Cost/unit (%)**
min	64	30	80	174	4,6%
nominal	80	40	100	220	5,9%
max	96	50	120	266	6,4%

Table 3.16. Cost allocation with used adhesive interval in production.

	Adhesive usage (mg)				
	STEP 1	**STEP 2**	**STEP 3**	**Total amount**	**Cost/unit (%)**
min	50	40	80	170	4,5%
nominal	**66**	**49,5**	**101,4**	**216,9**	**5,4%**
max	80	60	120	260	6,3%

Currently Axis pays a fixed fee for the push out testing which constitutes 6,8% of the cost for an OPTICAL UNIT. *Table 3.17* compares the test frequency used by the EMS to the test frequency found in **3.8.2 Push Out-Tests data analysis** and their respective impact on total cost. It becomes clear that Axis pays for push out tests that are never performed.

Table 3.17. Comparison Push out test cost calculation.

	Test Frequency			
	STEP 1	**STEP 2**	**STEP 3**	**Cost/unit (%)**
EMS Calculated	2,4%	2,8%	4,6%	6,8%
Actual	1,7%	1,8%	1,0%	2,4%

3.8.4 Process and Quality Control

Adhesive weight control is currently performed on every PCB ASS. It is understandable that it is considered necessary with manual dispensing, but the tests does not tell much about the process performance in general. The adhesive weight control only checks that the total amount is correct but not accuracy of the placement. With the varying performance of the dispensers it is technically possible for excessive amount of adhesive to be dispensed in some areas and compensated by insufficient amount in other which will render a passing result in the control even though the part is faulty. The process is hence fully operator dependent.

The UV-oven is today used as a safety precaution if the adhesive is not fully cured during the IBAS process. All completed OPTICAL MODULES are after cured due to the uncertainty and lack of control of the process. If greater control of the process can be achieved the after curing can be removed and the cycle time can be further reduced.

3.8.5 Yield

Analysis of the histograms show that each step is performing with yield above 95% which is acceptable results but with room for improvements. Yield is in this thesis defined as the percent of units that pass a certain control point. PU-tests indicate that problems caused by the optical module are mainly focus problems, blemish on the sensor and D-N FILTER. Blemish is dirt which most likely comes from particles in the clean room where the sensor film-cover is removed and the optical module is completed. Another theory is that the protective film on the sensor leaves residue when removed causing the blemish problems. The focus problem is most likely due to some type of change in relative position between optics and sensor after the IBAS process and final assembly of the camera. The IBAS process checks blemish and corrects focus and proper alignment but the sensitivity in the IBAS might be lower than in PU-tests.

The completed modules are not checked after the IBAS process before going to final assembly resulting in an uncertainty where the problems arise. The first time the yield is measured for the complete optical module is when the finished product is tested in final PU. Since the module have gone through a number of steps it is difficult to find the source of the error. Error codes from fails in PU-test describes what has failed, not what caused it.

4 Method

This chapter describes how the adhesive and dispensers are tested and evaluated which are used for design of the new process. The testing is done to answer three important questions. What measures are important to control to get repeatable results, how does the operator and equipment influence the process and is it possible to change the adhesive used today? The testing of the parameters are thereby done using both adhesives. During the testing observations where made which led to other tests were set up. The tests have been discussed and designed with the help from Thomas Elfström.

4.1 Equipment

The equipment used during the testing is presented here. All equipment except for the automated dispenser is available and used by the EMS.

4.1.1 Automated dispensing system (ADS)

Two types of dispensers have been used for evaluation of the current process and testing of the new. Adhesive tubes used in these tests are the original tubes supplied by Dymax and Delo.

A Loctite 97006 dispenser was used to evaluate the current manual process; the same dispenser is used in production at the manufacturer. The dispenser which have been used for the tests of the new system is a Musashi super Sigma CM2 dispenser. Temperature control of the adhesive is achieved by a Musashi Peltiermaster TCU-05F2 control unit, keeping the adhesive at 34 degrease Celsius. For placement of the adhesive a 3-axis Musashi Shotmini 200 have been used. It is an automatic adhesive application system with a table surface area of 150x150 mm and an application precision of 0,1 mm according to supplier specifications.

4.1.2 UV-light

Curing of the adhesive was done using three different equipment depending on the parts bonded.

Step 1: both a DELOLUX 80 controlled by a DELO-UNIPRO Light station and DYMAX ECE Zip UV oven.

Step 2: DELOLUX 80 controlled by a DELO-UNIPRO Light station

Step 3: Panasonic 365 nm UV-Lamps controlled by a Panasonic station.

4.1.3 Push-out testing

Axis current method for validation of the process is push-out testing. It is performed in all three steps for the Hedwig camera. The part that is to be tested is placed and secured in a fixture, generating the same load case for every test, see Figure 4.1.

One of the parts are fixed while the other part can be moved in the push direction. The push out probe connected to the force gauge is then moved with a speed of 5 mm/min pushing the cup, lens or PCB ASS from the bonded part.

Figure 4.1. Illustration of a push-out test for step 1.

The Push out machine used for the tests was a Mecmesin Multitest-dv and the force gauge is a Mecmesin AFG 500N. The position and load of the probe is logged and plotted in an excel files to later be analyzed.

4.2 Fixed parameters

For the adhesive system, there are parameters that can be changed quite easily, such as cleaning the parts and wetting forces. Material choice and design is harder and more complicated to change and are thereby considered to be fixed parameters in this thesis. The focus is not to change them but to design the process after them.

4.2.1 Adhesive system

The first thing to establish is if the adhesive system is favorable. The surface tensions of the ingoing parts and adhesive determines how strong the bond possibly can become. Other parameters, such as wetting and cleanliness of the parts increase or decrease the joint strength, but without a favorable system the adhesive won't work. Obtaining data for exact surface tensions on materials is hard, and since the PCB and adhesive suppliers are reluctant to share this data analytical testing is necessary to establish if an adhesive system is favorable.

4.2.2 Optimal Amount of adhesive to use

All parts are designed with cavities to hold the adhesive. From this, the theoretical amount of adhesive can easily be calculated using a CAD program. In this case CREO 3.0 was used and the theoretical values are presented in

. If more adhesive than the theoretical amount is used, the exceeding amount will overflow and not affect the joint. On the other hand, if less than the theoretical amount is used, the cavity will not be fully filled, resulting in a weaker bond. Parts where bonded using the theoretical amount of adhesive and the strength of the bond where then measured through push-out tests. Both strength and consistency of the adhesive joint is analyzed. The main aspect is that the same amount of adhesive is in every insert since the adhesive shrinks when cured. As Hedwig has a fixed focus lens, it is important to obtain correct focus before the adhesive is cured. As of today, IBAS compensate a fixed distance for the shrinkage based on an average amount of adhesive. Shrinkage is proportional to the volume of adhesive used. With a better control of the amount of adhesive, IBAS can better compensate for the shrinkage. Further, the amount of adhesive between each cup on a PCB is also of importance. The shrinkage in each individual cup might warp the lens in relation to the sensor if there is a big difference in over the four cups.

Table 4.1. Theoretical amount and placement of the adhesive using.

Step	***Amount of adhesive***	***Form of adhesive line***
1	7 ml/ADHESIVE INSERT	Circle with diameter 5,5 mm, line width 1 mm, height 0,5 mm
2	10 ml/side	Arc with radius 6,2 mm, segment angle 40 degrees, height 0,5 mm, line width 1 mm
3	17 ml/cup	Fill of a cavity where the pin is inserted. Height 2,25 mm

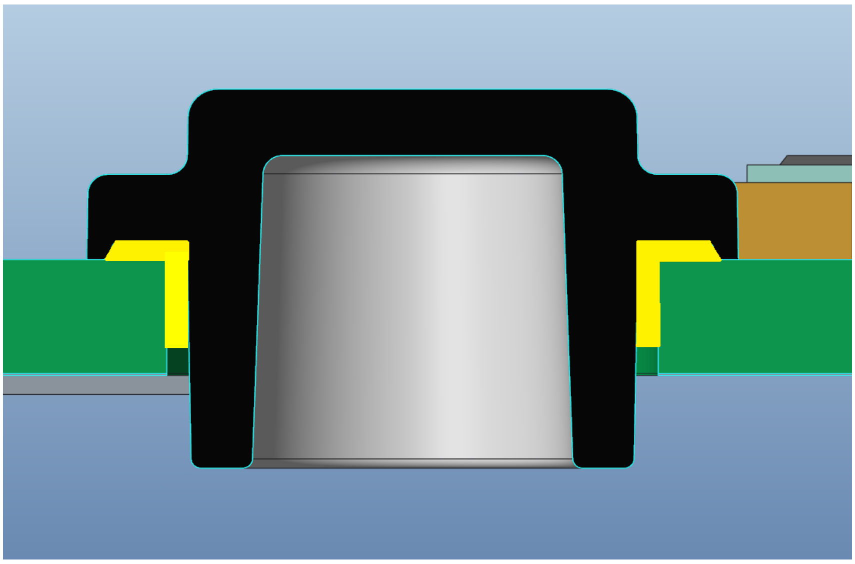


Figure 4.2. 7 ml of adhesive is needed to fill the cavity for the inserts.

4.3 Variable parameters

Variable parameters are easily changed if necessary. Cleanliness, wetting time and wetting forces have an impact on the adhesive joint. However, increased process time for cleaning and wetting needs to be motivated, and hence the impact of these parameters needs to be analyzed.

4.3.1 Cleanliness

Since it is unclear how contaminated the parts are when arriving to the stations for assembly the cleanliness of the parts needs to be tested. Small particles have small effect on the adhesive joint while grease, fat and release agents have greater impact. The first step is to test all the ingoing parts for the latter three contaminates. This is done by performing a Varnish Spreading Deficiency test (VSD). Parts are placed on a clean glass plate and rinsed with Isopropanol which transfers the fat, grease and agents onto the glass. The parts are then removed and the solvent evaporates. The plate is sprayed with regular water based spray paint. How contaminated the parts are can be seen since the paint do not stick to the areas on the glass where contaminates are present.

When it is established which parts that are contaminated, the effect of contaminants on the adhesive bond needs to be established. It is done by performing each process step again and measure the strength of the bond under the new conditions with push out tests.

4.3.2 Wetting time

From previous observations at Axis it have been seen that Photobond requires longer time to reach wetting equilibria. Hence the adhesives ability to wet the substrates needs to be examined. Drops of both adhesives are dispensed on separate PCBs and cured after a set amount of time have past, analyzing the wetting times influence on the system. The first drop will be cured directly after dispensing, and then drops will be cured after 5, 10, 15 and 30 minutes. Effects from wetting through applied force is tested by dispensing a drop, spreading it over the surface and then curing the adhesive. The wetting angle was then analyzed using an Alicona infinite Focus microscope.

After the wetting angles have been analyzed practical testing can be made to examine if Photobond can replace OP 67 as the adhesive for the process. How different curing times and intensity affect the adhesive is unknown, but Delo recommend low intensity and longer curing time [1]. Longer curing time and wetting time increase the cycle time, which is not a sought-after result. Hence, both wetting time and curing time will be tested for Step 1, 2 and 3.

4.4 Equipment and operator

How the dispenser and operator interact and affect the adhesive joint is today unknown. What is known is that the amount of adhesive varies from unit to unit. What causes the variation is not established and to achieve a repeatable process the causes must to be found. Even when the amount of adhesive is stable, the precision is equally important for a repeatable and strong joint. Hence the precision of the operator is crucial for the adhesive joint strength.

4.4.1 Dispenser tolerance

Dispensed amount of adhesive affect both the product cost and the strength of the bond up to some extent. Knowing the dispensers tolerance span allows for the theoretical amount to be offset which ensures that minimal quantity of adhesive always is used.

To establish the dispenser tolerance, the operator needs to be taken out of the equation. For the hand-held dispenser, the nozzle was fixated in a jig and 30 drops of adhesive was dispensed. The first drop measured was then the reference amount and the rest of the 29 drops were compared to the first one. Each droplet was weighed and the amount recorded. Between every drop, the needle tip was wiped clean.

The influence of the needle and tube was also investigated. Using the automated system 15 dots of adhesive was dispensed and individually measured. After 15 drops, the tube was removed from the machine and needle discarded. The tube was then rested for 15 minutes to normalize the pressure. A new needle was then fitted and 15 new drops dispensed. Three different needles where tested on the same tube with the same program and pressure settings on the automated system.

4.4.2 Operator

To analyze the operators' influence on the process three different operators dispensed 30 dots of adhesive without calibrating the dispenser in between. If the variation in weight between the drops for one operator is high, the process is considered to not be repetitive. Reproducibility is how the process is affected by different operators and is measured by the variations between sets of measured points performed by different operators. The reproducibility is considered to be high if the variation between the series of dispensed dots are low, implying that the operators effect on the process is low.

Precision when dispensing the adhesive is both difficult and hard to measure since both the parts and the amount of adhesive are very small. The only way to establish the precision factor is by doing push out tests on units where the adhesive was dispensed with the automated system and comparing the results to the current process.

4.5 Adhesives

The adhesive tubes used affect the dispensed amount while the adhesive itself have an internal variation in bond quality. The adhesives used are thermos setting plastics that is polymerized when cured. The crosslinks in the adhesive build up the bond strength. Depending on how the crosslinks are formed, the bond strength varies.

4.6 Test set-up

To establish the new process and process parameters, testing and validation have been divided into two stages. Ten units were tested for every parameter configuration. If the tests gave the desired results, 15 more units were tested for stability evaluation. The amount of units for the tests were set regarding time frame of the thesis and budget.

The first stage is to see how the use of the automatic dispensing system would influence the adhesive joint. When dispensed by the robot, the variations in precision and amount of adhesive should be greatly reduced, and the variations in push out forces should therefore be a result of the ingoing parts cleanliness and the adhesives properties. The amount of parts tested for stage 1 can be seen in **Appendix B** .The adhesive used in stage 1 is OP 67 which is used in the current process which a density of 1,14 mg/ml. The density of the adhesive is important for validating that the correct amount of adhesive is used by controlling the weight. The form and thereby the dispensed adhesive string is controlled by pressure, time and position of the needle. However, the volume is difficult to measure since the dimensions are very small. The volume on the other hand can easily be measured using a high tolerance scale measuring down to 0,1 mg. Hence the volume is controlled by weight and ocular inspection. For step 1 external wetting forces have been used to eliminate the effect of wetting time. To properly wet the PCB and cup a small cylinder have been used to push the flange of the cup onto the PCB with a twisting motion. This method is used in the current process.

From the VSD tests it was concluded that the PCB A build up some sort of contaminants when being soldered. How these contaminants affect the adhesive joint was analyzed by bonding 8 PCB As without cleaning and analyzing the push-out forces.

Stage 2 is to see if OP 67 can be changed to Photobond and what parameters need to be adjusted for the new adhesive. In **Appendix B** all the test carried out using Photobond can be seen. Density of Photobond is 1,69 mg/ml which gave the controlled weight of adhesive for every test.

5 Improvement process

In this chapter the results from the different tests will be presented along with comments and analysis of the results.

5.1 Dispenser evaluation

Variations in the dispensed amount was tested for 5.7 mg adhesive with both dispensers. **Fel! Hittar inte referenskälla.** shows the variations for the Loctite dispenser compared to the Musashi sigma dispenser for the same amount adhesive. Figure 5.2 is a further investigation for the automated system. Figure 5.3 shows how the dispensed amount is dependent on pressure build-up in the adhesive tubes and the needle.

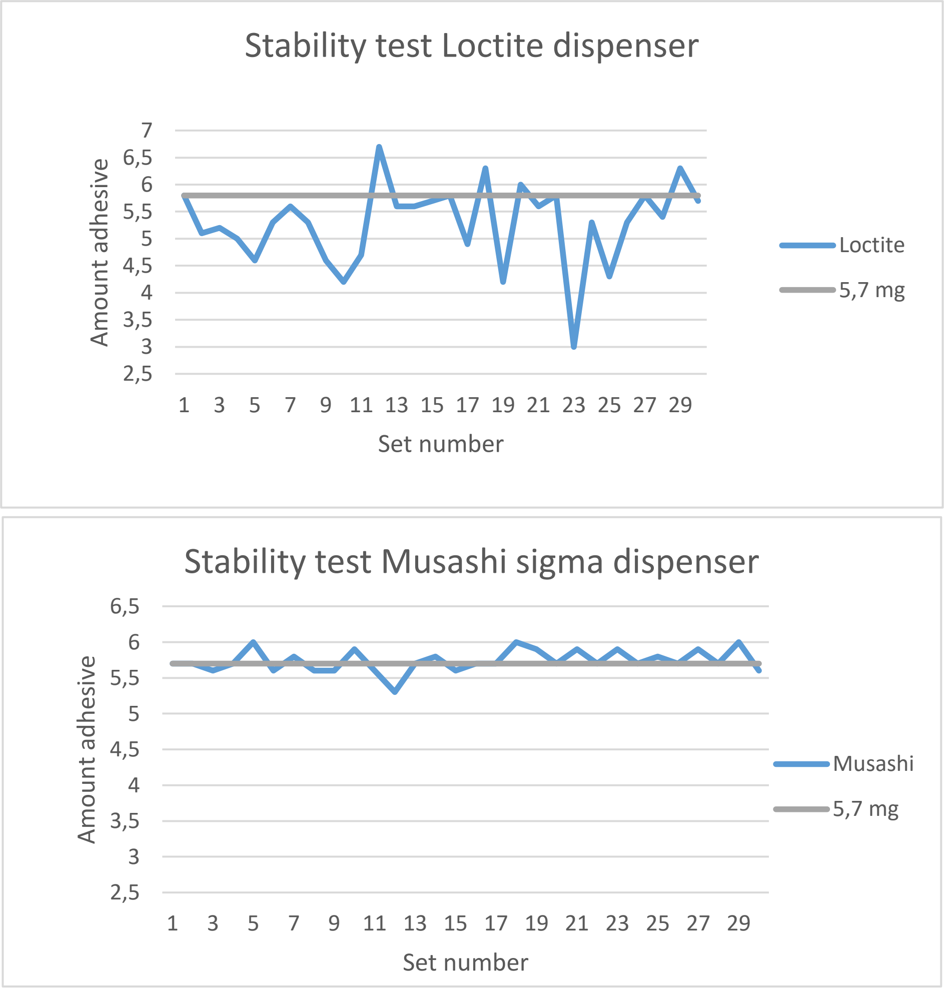


Figure 5.1 Variations in dispensed amount using the hand held Loctite dispenser and the Musashi sigma dispenser for OP 67

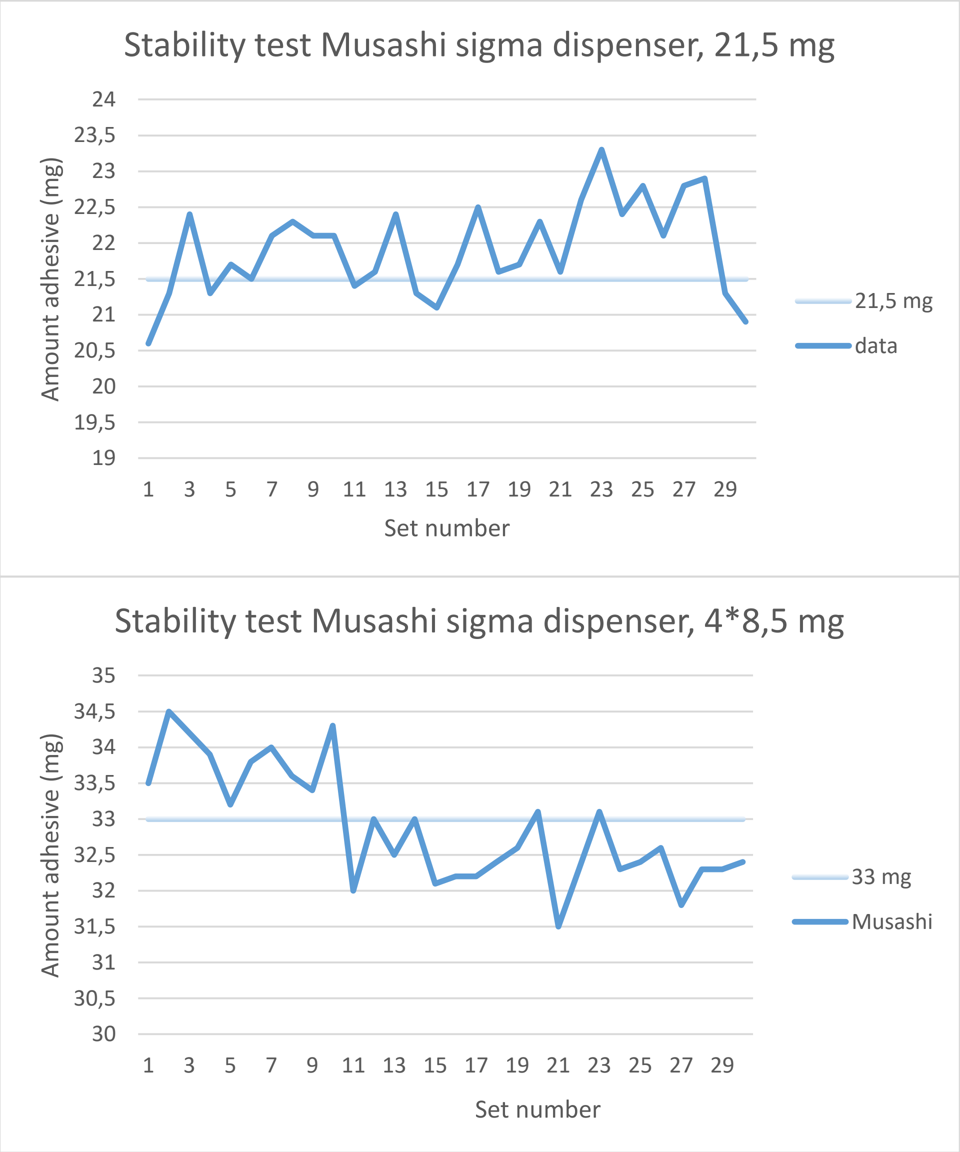


Figure 5.2. Stability test for Musashi sigma dispenser using the automated system. The variations in the system is roughly +/- 5 % of the adhesive weight.

Stability test show that the variations in dispensed amount from the Loctite dispenser is in average 20% while for the sigma dispenser the amount differs less than 5%. For the Musashi stability tests seen in the lower diagram in Figure 5.2. The needle was changed after 10 sets. The diagram shows that the dispensed amount was reduced due to the needle change which is shown again in Figure 5.3. It was later observed during the testing that each individual needle had impact on the dispensed amount by up to 10% resulting in that the dispensing speed or pressure had to be adjusted whenever a new needle was used.

Observations were also made that the dispensed amount have a greater variation the first sets when a new tube was used. The amount decrease over time and stabilizes after some time, as seen in Figure 5.3. The first set was done with a tube that had been rested for over a day. Between each set the tube was rested for 15 minutes. The decrease in dispensed amount is greater for the first set while the decrease is similar for the other two sets with decreasing about 2 mg over 15 sets. This is probably due to an internal pressure building up in the adhesive and when the tube is rested, the pressure decrease, but to fully normalize to air pressure it need to be rested for longer than 15 minutes. The theory is strengthened by the fact that adhesive continuously dripped from the needle after dispensing was completed. The amount that dripped was dependent on the tube, since some tubes dripped a lot more than others. The leakage was controlled by the vacuum on the dispenser.

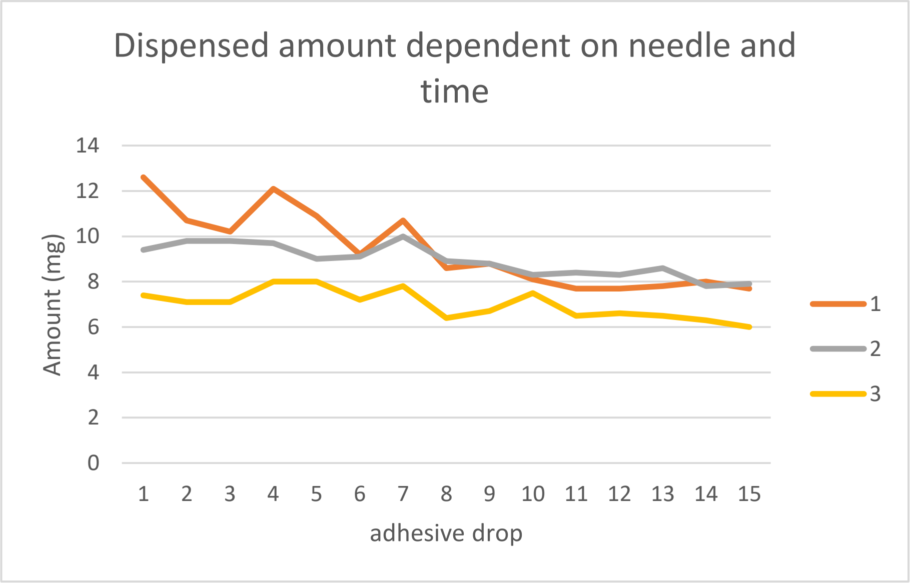


Figure 5.3. Dispensed amount measured for 15 drops with three different needles. Between each needle change the tube was rested for 15 minutes letting the pressure normalize.

5.2 Operators influence

Figure 5.4 shows how the current dispensing process is influenced by the operator. The reproducibility and repetitiveness of the system is considered to be very low.

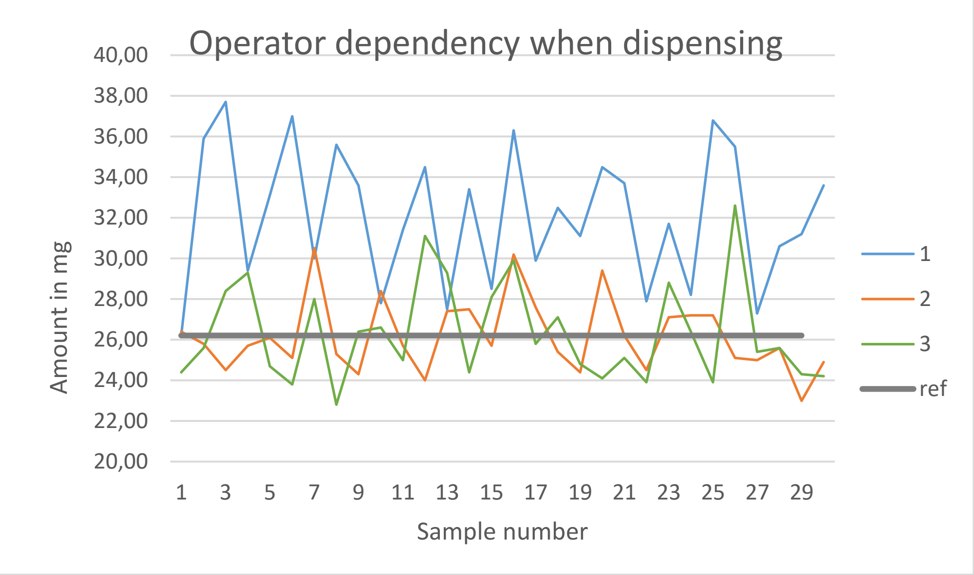


Figure 5.4. Operators influence of dispensed amount regarding OP 67 and using a Loctite hand dispenser. Reference value was 26,2 mg.

Table 5.1. Mean and standard deviation of the amount of adhesive from all three operators.

	Value	*Unit*
Mean	28,19	mg
STD	3,75	mg

The operators influence on the process is also significant and depending on the operator and dispenser the variations in dispensed amount can be as much as 40%. Depending on the operator, both the amplitude and mean of the dispensed amount is affected. This results in a low repeatability for the single operator and also low reproducibility for the production line since there is rotation of operators. However, with proper training the variations in adhesive amount can min lowered. Operator 1 both have a greater variation and is also offset from the reference value compared to operator 2 and 3.

5.3 Varnish spreading deficiency test

Figure 5.5 to Figure 5.8 show VSD-tests for ADHESIVE INSERTS, PCB A and PCB RAW, and LENS HOLDER.

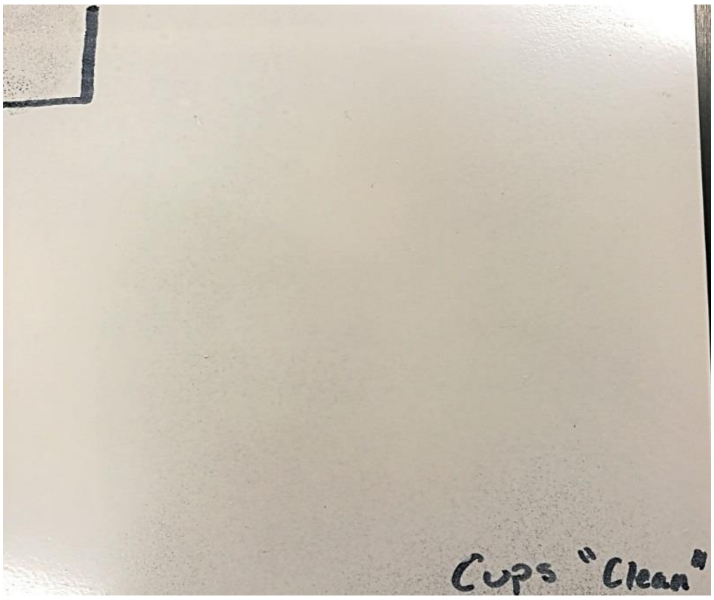


Figure 5.5. VSD test for INSERTS ADHESIVES. As can be seen, no signs of release agents or fats are present on the parts.

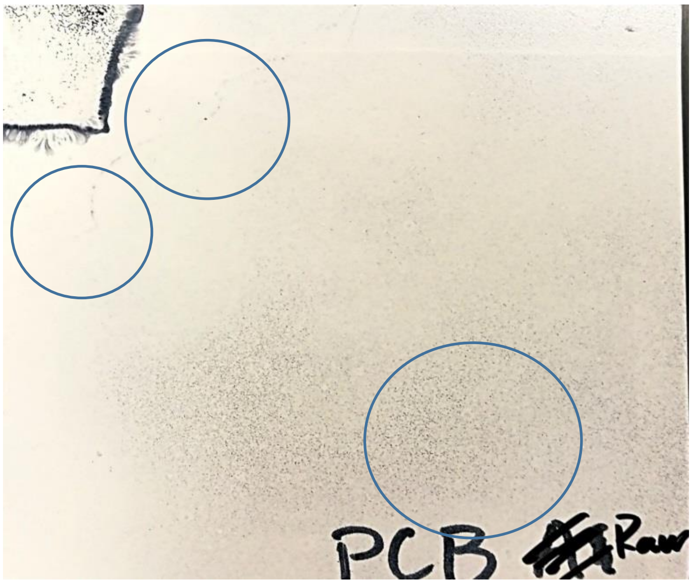


Figure 5.6. VSD teset for raw PCB Raw that have not passed through the soldering oven. Some traces of release agents or fats can be seen in the left corner and bottom centre.

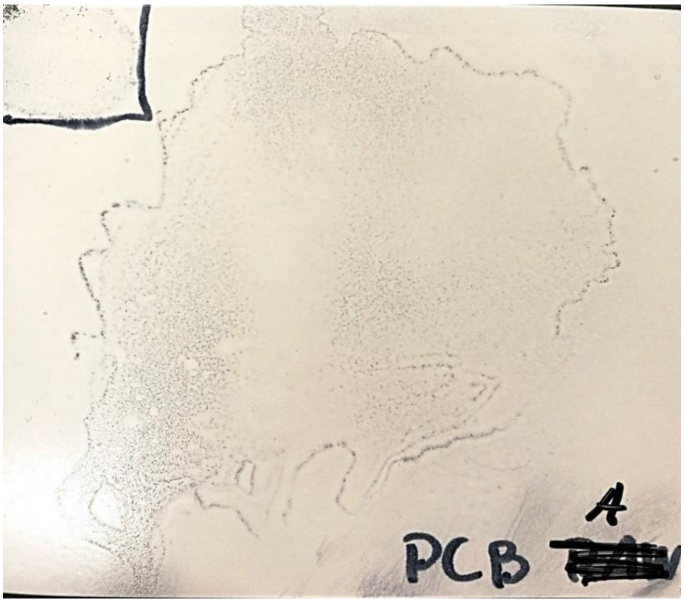


Figure 5.7. VSD test for PCB A's that have been soldered. It can be seen that there is some sort of release agents or flux present on the PCB's.

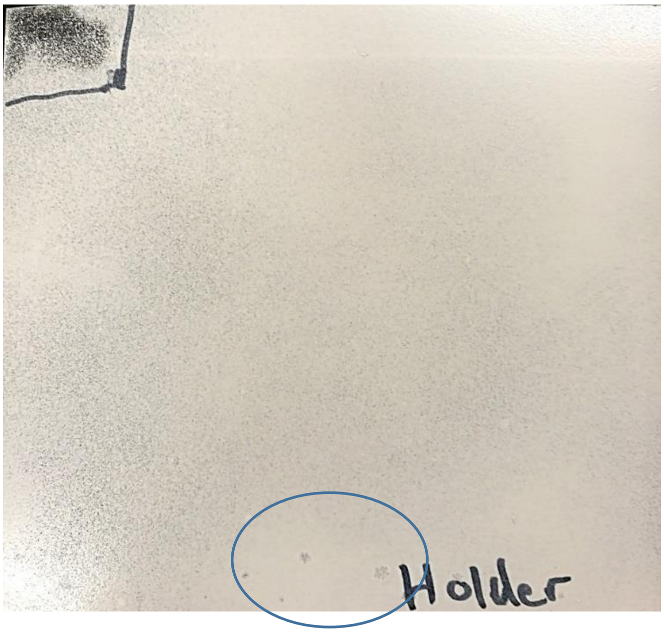


Figure 5.8. VSD test for LENS HOLDERS. As can be seen, some faint traces of contaminates are present on the bottom of the sheet but no major signs of release agents or fats are present on the parts.

From the VSD-test all tested parts were almost free from contaminates except from the PCB A and PCB Raw. The presence of contaminate on the PCB Raw is less than that on the PCB A. However, flux on the PCB A does not affect the push-out forces regarding Photobond and OP 67 later shown in **5.4.1 Step 1 using OP 67** and **5.5.1 Step 1 using Photobond**.

5.4 Evaluation of Dymax OP 67

OP 67 was used to bond units for step 1 and 2 according to .

5.4.1 Step 1 using OP 67

Inserts where bonded to the PCB's according to the set-up presented in **Appendix B.** The variations in push-out forces is presented in Figure 5.9 to Figure 5.13. Statistical data is presented in Table 5.2, Table 5.3 and Table 5.4. Detailed pictures of the PCB's and cups can be seen in **Appendix C.** By fixture cured the part was cured incapsuled by a fixture. When open cured the pcd was placed directly under a UV-lamp.

Table 5.2. Statistical parameters for the histogram in Figure 5.9.

	Value	***Unit***
Mean	151,39	N
STD	37,10	N
5%-percentile	72,05	N

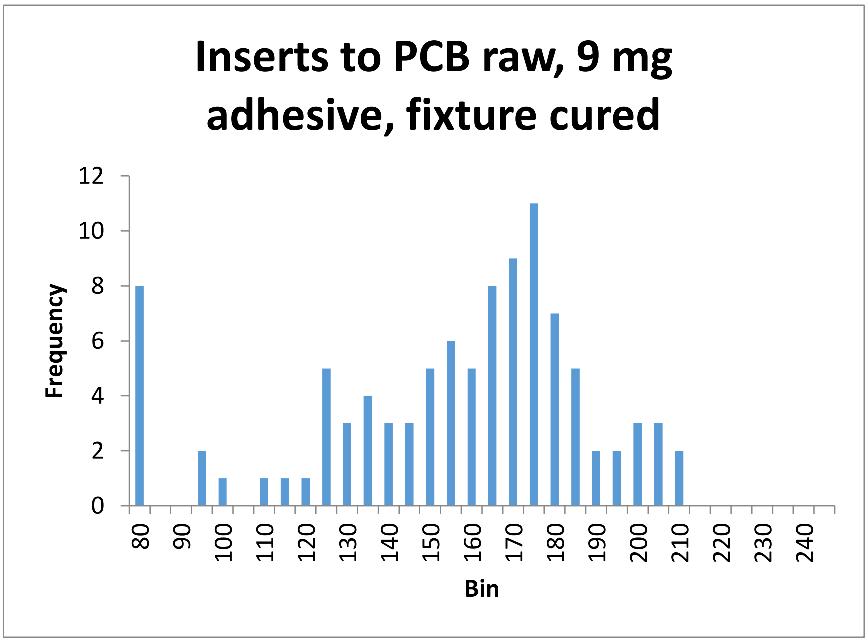


Figure 5.9. Histogram of the push-out forces when inserts have been bonded to PCB raw using 9 mg OP 67 adhesive and cured in the current fixture.

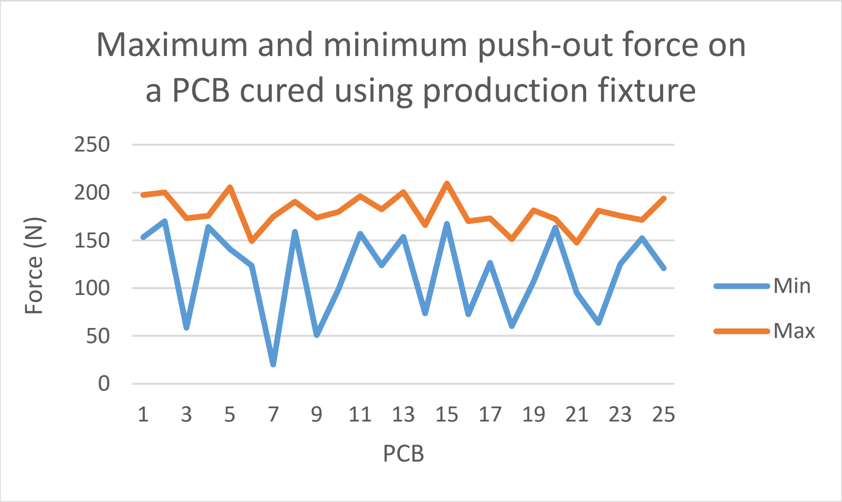


Figure 5.10. Difference between maximum and minimum push-out force for 25 PCB's that have been cured using the current curing setup.

Figure 5.11 show the variations in push-out forces for inserts bonded to PCB's with 9 mg adhesive cured without the fixture. Figure 5.12 show how the maximum and minimum push-out forces on each PCB are related. 8 PCB A's were bonded using 9 mg OP 67 and the push out values are shown in Figure 5.13 and Table 5.4.

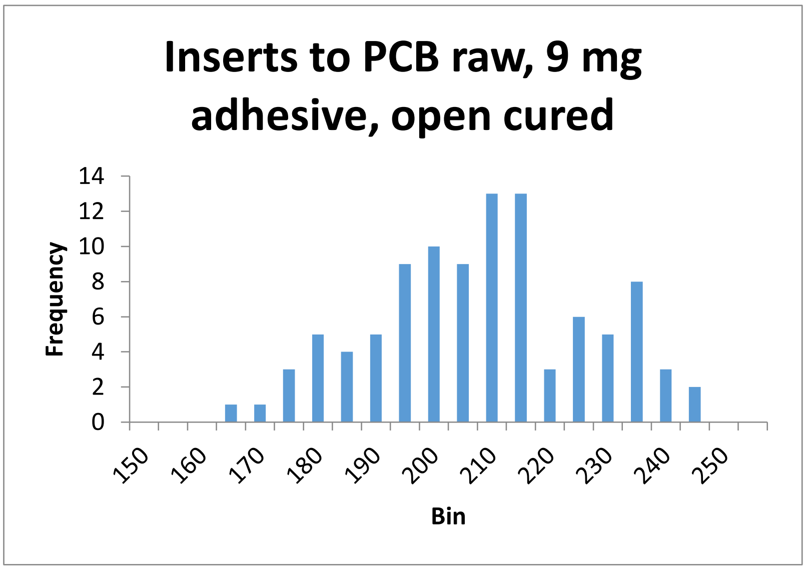


Figure 5.11. Histogram of the push-out forces when inserts have been bonded to PCB raw using 9 mg OP 67 adhesive and cured with the inserts flange and adhesive exposed.

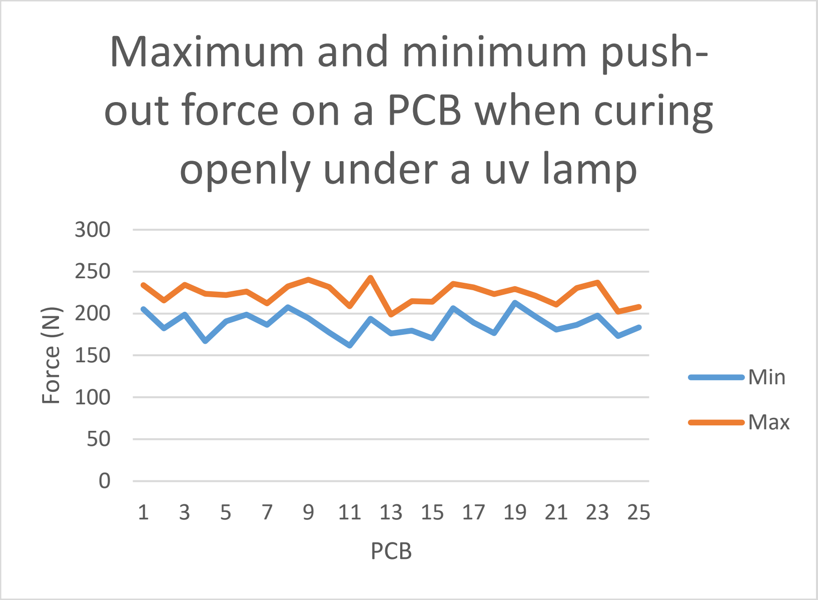


Figure 5.12. Difference between maximum and minimum push-out force for 25 PCB's that have been cured openly under a UV-lamp.

Table 5.3. Statistical parameters for the histogram in Figure 5.11.

	Value	***Unit***
Mean	205,79	N
STD	18,19	N
5%-percentile	175,86	N

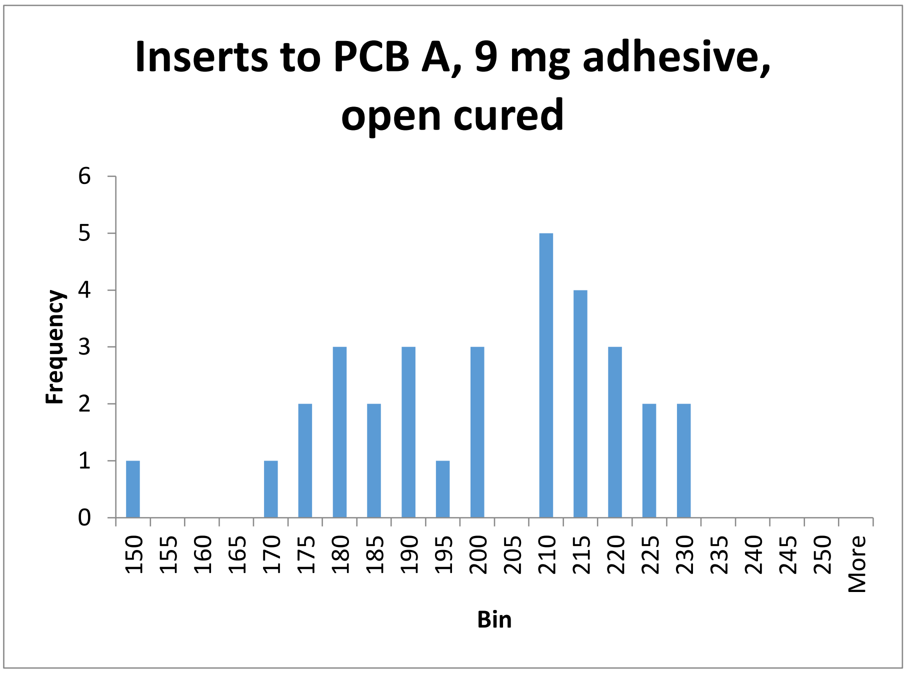


Figure 5.13. Histogram of the push-out forces when inserts have been bonded to PCB A using 9 mg OP 67 adhesive and cured with the inserts flange and adhesive exposed. The PCB A have not been cleaned before the bonding.

Table 5.4. Statistical parameters for the histogram in Figure 5.13.

	Value	***Unit***
Mean	198,12	N
STD	19,76	N
5%-percentile	169,24	N

Curing of the adhesive is today carried out using a fixture and UV-light, see Figure 5.14. When using the fixture, the adhesive is partly covered by the aluminum tube in which the cup rests which may prevent light from activating the adhesive in those specific areas. The ADHESIVE INSERTS are made of clear PMMA which absorbs some UV-light but will let most of the light through which have led to the design of the fixture. When curing 9 mg of OP 67 adhesive, variable results were obtained. When closer examining the adhesive it could be seen that the color of the adhesive string was inconsistent. In some places the adhesive was semi-transparent and had a dull gray color while in other places the adhesive was white and opaque. When a tweezer was used to see if the adhesive was soft or hard the gray adhesive was easily removed and a little elastic, coming off in big pieces. For the whiter adhesive it was more brittle and harder to remove, and crumbling when enough force was applied leading to the theory that the gray adhesive was not completely cured. The brittle white adhesive consistently had higher push out values than the grayer. The inconsistency in curing led to the test where the adhesive was cured without a fixture, see Figure 5.15. The new curing set-up both increased the mean push-out force by 36% while decreasing the standard deviation by 49%. More is that the difference between the maximum and minimum push-out force is less and the forces follow each other much closer. Compared to the old curing set-up, there seem to be some sort of correlation between minimum and maximum for every PCB for the new curing set-up. Contaminate on the PCB A did not affect the push-out forces except for one measurement.

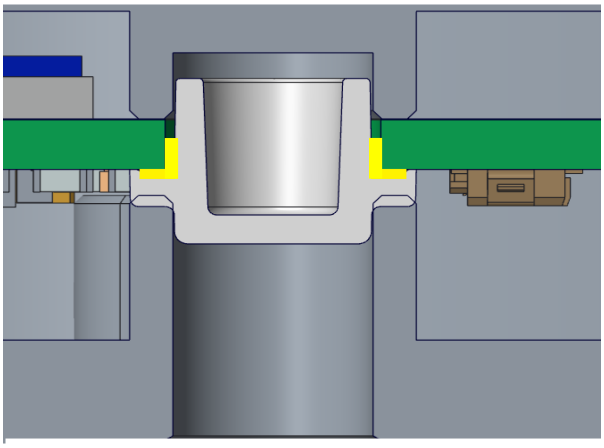


Figure 5.14. Current fixture used when curing the adhesive for step 1. The aluminum fixture covers part of the adhesive, resulting in variable curing.

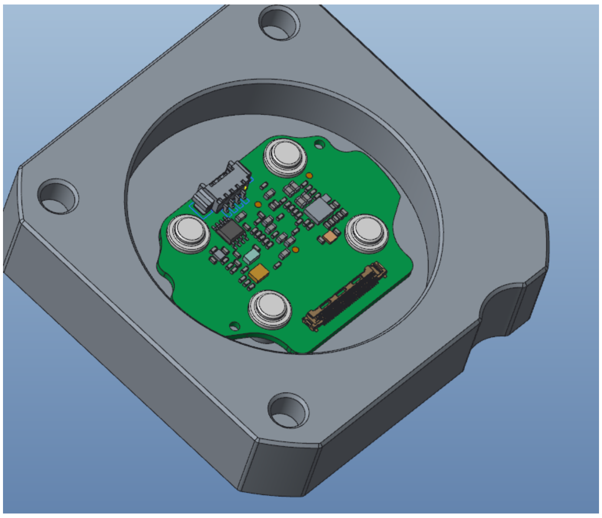


Figure 5.15. The top part of the fixture which is used to hold the PCB. The bottom part is removed exposing the entire cup to the UV-light.

5.4.2 STEP 2 using OP 67

25 Lenses were bonded and push-out forces measured. Distribution of the push-out forces and statistical parameters are presented in
Table 5.5 and Figure 5.16.

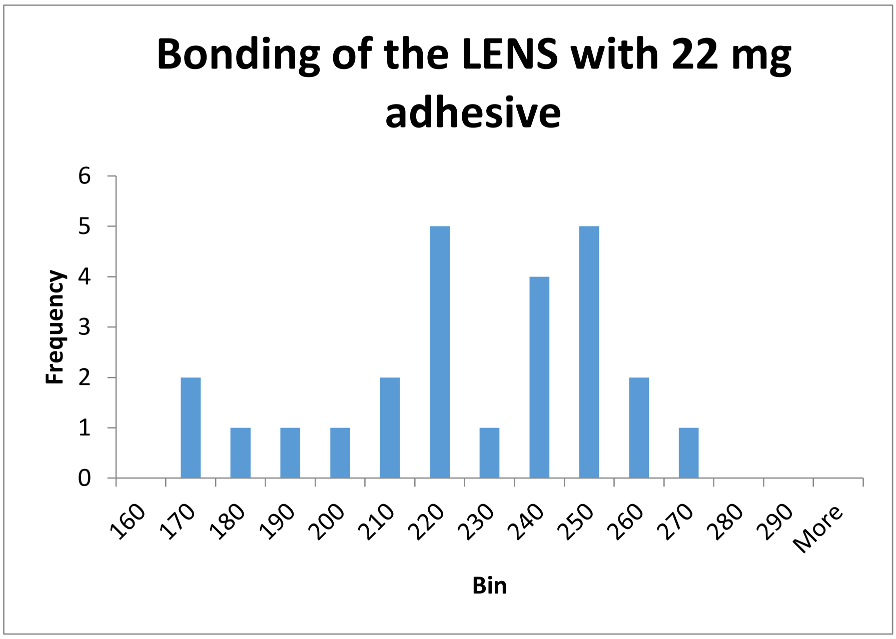


Figure 5.14. Push-out forces for bonding of the LENS using 22 mg OP 67 adhesive (11 on either side).

Table 5.5. Statistical parameters for the distribution in Figure 5.16.

	Value	***Unit***
Mean	221,56	N
STD	26,69	N
5%-percentile	169,56	N

With the increase in positioning when dispensing with the automated system the amount adhesive can be reduced by 50% for step 2. The mean push-out force decrease by 20%, but more important is that the variance decrease by 43% due to the fact that adhesive is at the correct spot. The decrease in mean push-out value will be discussed later. It was established that with the use of the Musashi sigma dispenser and robotic system the adhesive amount can be reduced by 50% for step 1 and 2 while also resulting in less variable push-out forces and thereby a more stable process.

5.5 Evaluation of Delo Photobond

Wetting angle measurements after controlled wetting time is presented in Table 5.6.

Table 5.6. Wetting angle for adhesives OP 67 and Photobond after different wetting times.

Wetting time	*OP 67*	*Photobond*
0	96,2	67,5
5	50	50,1
10	51	47,3
15	45,7	48,3
30	41,0	44,3
Spread sample	20,3	25,7

Comparing photobond to OP 67 it can be concluded that initially photobond wet the substrate better than OP 67, in this case a PCB. The initial wetting can be related to the lower viscosity of photobond and it can be seen that over time OP 67 spread over the surface slightly better that Photobond. Even more interesting is the wetting angle when external forces have been applied to spread the adhesive over the PCB. The tests show that both of the adhesives work favorable with the PCB's. The other ingoing parts are made of fiber reinforced PC and PMMA which are in the upper spectrum of low energy surfaces, and aluminums, which is a high energy material. The coatings on the PCB's have roughly the same or lower surface energy than PC and PMMA, leading to the conclusion that both the adhesives create a favorable system with all the ingoing parts. OP 67 theoretically should perform slightly better than photobond if only the wetting angle criteria is taken into account.

5.5.1 Step 1 using Photobond

Inserts where bonded to the PCB's according to the set-up presented in **Appendix B**. The variations in push-out forces is presented in Figure 5.16 to Figure 5.22. Statistical parameters are presented in
Table 5.7. to Table 5.13. Detailed pictures of the PCB's and cups can be seen in **Appendix C**.

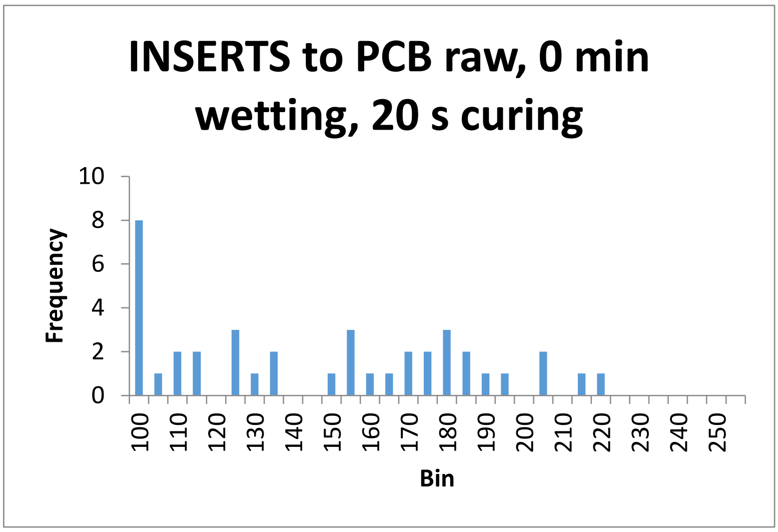


Figure 5.16. Histogram of the push-out forces when inserts have been bonded to PCB raw using 11 mg Photobond adhesive and cured for 20 seconds without wetting time..

Table 5.7. Statistical parameters for the Histogram in Figure 5.16.

	Value	***Unit***
Mean	140,34	N
STD	44,46	N
5%-percentile	69,75	N

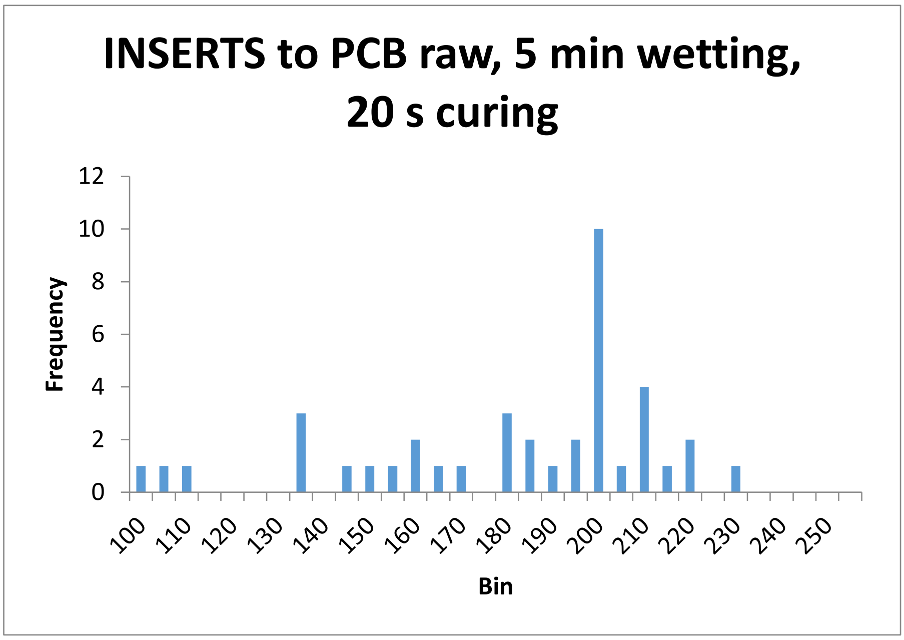


Figure 5.17. Histogram of the push-out forces when inserts have been bonded to PCB raw using 11 mg Photobond adhesive and cured for 20 seconds with 5 minutes of wetting time.

Table 5.8. Statistical parameters for the Histogram in Figure 5.17.

	Value	***Unit***
mean	177,88	N
std	33,88	N
5%-percentile	105,12	N

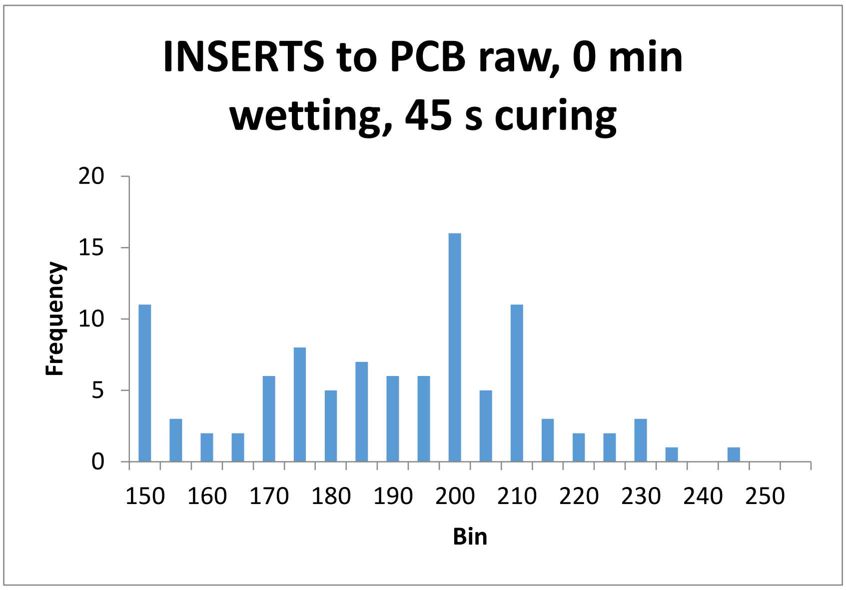


Figure 5.18. Histogram of the push-out forces when inserts have been bonded to PCB raw using 11 mg Photobond adhesive and cured for 45 seconds with 0 minutes of wetting time.

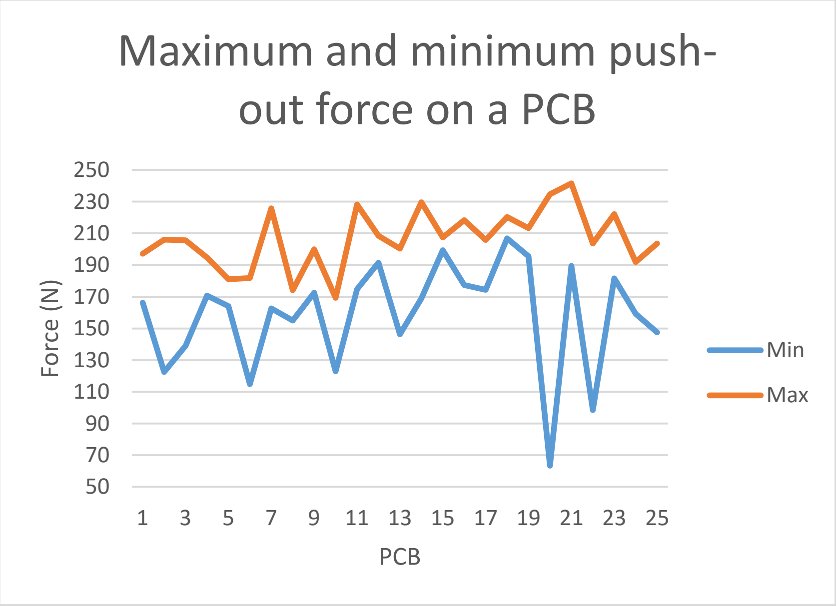


Figure 5.19. Difference between maximum and minimum push-out force for 25 PCB's that have been bonded using Photobond and cured for 45 seconds after 0 minutes of wetting.

Table 5.9. Statistical parameters for the Histogram in Figure 5.18.

	Value	***Unit***
Mean	184,37	N
STD	29,10	N
5%-percentile	125,08	N

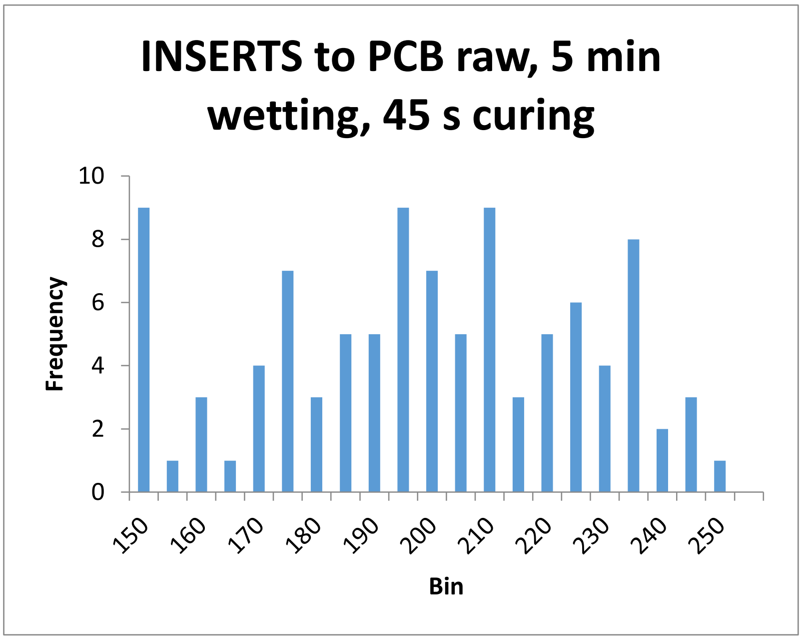


Figure 5.20. Histogram of the push-out forces when inserts have been bonded to PCB raw using 11 mg Photobond adhesive and cured for 45 seconds with 5 minutes of wetting time.

Table 5.10. Statistical parameters for the Histogram in Figure 5.20.

	Value	***Unit***
Mean	194,92	N
STD	30,92	N
5%-percentile	134,62	N

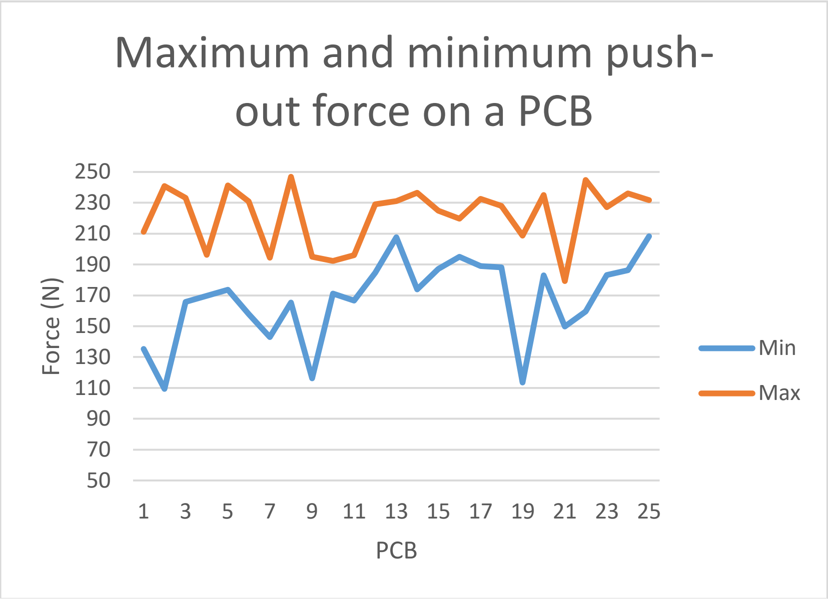


Figure 5.21. Difference between maximum and minimum push-out force for 25 PCB's that have been bonded using Photobond and cured for 45 seconds after 5 minutes of wetting.

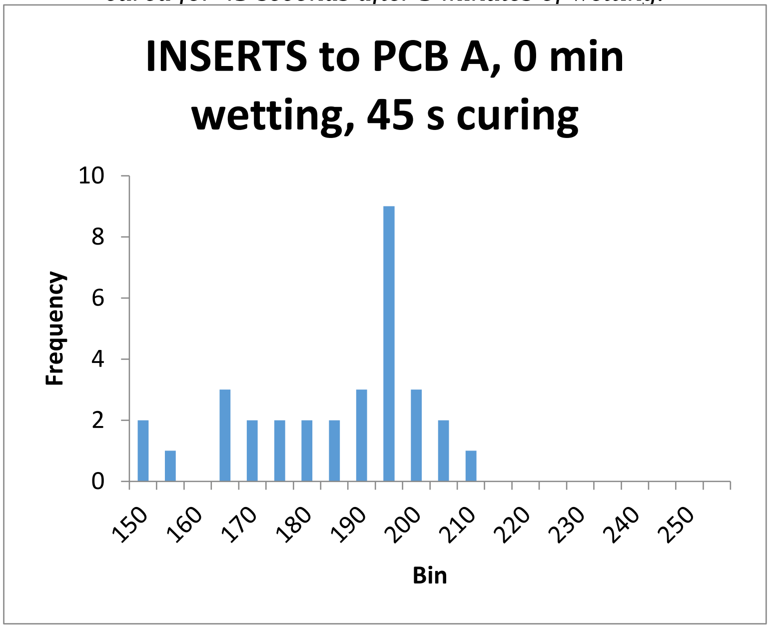


Figure 5.22. Histogram of the push-out forces when inserts have been bonded to PCB A using 11 mg Photobond adhesive and cured for 45 seconds with 0 minutes of wetting time. It can be seen that the contaminates on the armed PCB does not affect the adhesive bond.

Table 5.11. Statistical parameters for the Histogram in Figure 5.22.

	Value	Unit
Mean	181,51	N
STD	18,03	N
5%-percentile	146,13	N

When bonding the cups to the PCB raw with photobond variable results were obtained when no wetting and 20 seconds curing time were used. When a wetting time of 5 minutes was used mean push-out value increased while the standard deviation decreased. The observations previously made that photobond needs longer time to reach wetting equilibria seems to be true. When increasing the curing time to 45 seconds both the samples that had no wetting time and 5 wetting time showed higher and less variable push-out forces than the samples cured for 20 seconds independent of wetting time. The increase in push-out forces raises the question if wetting of the substrates or curing of the adhesive is the main factor affecting the push-out forces. For both 20 and 45 seconds of curing, the samples that had been allowed to wet for 5 minutes gave better results than the samples that where directly cured after dispensing. The difference between wetted samples and un-wetted samples decreased with an increase in curing time. For samples cured for 20 seconds the mean push-out force increased with 27% after 5 minutes of wetting compared to only 6% when the samples were cured for 45 seconds. When comparing photobond to OP 67 there is less of a trend when it comes to the minimum and maximum push-out force on each individual PCB.

During push-out tests on the cups it was discovered that the cups broke before the adhesive joint ruptured. When forces exceeded 190 N it was common that the insert was damaged. To better analyze the Push-out forces, all forces exceeding 190 N were set to 190 N. This gave a better overview of the lower forces influence of the stability. The adjusted data is presented in Table 5.12.

Table 5.12. Mean push-out force, standard deviation and 5 % quantile when the push-out values have been adjusted for broken cups.

	1	2	3	4	5	6	Unit
Curing time	45	45	20	20	FIXTURE	OPEN	s
Wetting	0	5	0	5	-	-	min
Adhesive	PB	PB	PB	PB	OP67	OP67	
Mean	176,5	179,9	135,5	171,1	150,4	187,9	N
STD	22,4	19,1	41,9	28,4	35,8	5,4	N
5%-quantile	125,1	134,6	69,8	105,1	72,1	176,0	N

During all the tests it became evident that small variations in amount of adhesive had small or none effect on the push-out forces. The automated systems increase in accuracy resulted in adhesive at the right places and better controlled curing proved to increase stability and push-out values. **Appendix D** shows 100 inserts bonded to 25 PCB raw with 5 mg OP 67 with the Musashi system. The adhesive was cured using a DELOLUX lamp but cured inside the fixture. The best push-out values achieved with only 5 mg adhesive was 168,4 N. The result is this case was variable with a high standard deviation, which could be because of the small amount of adhesive or the fixture curing.

5.5.2 Step 2 using Photobond

25 Lenses were bonded using 32 mg of Delo Photobond adhesive and push-out forces measured. Distribution of the push-out forces and statistical parameters are presented in Figure 5.23, Figure 5.24, Table 5.13 and Table 5.14.

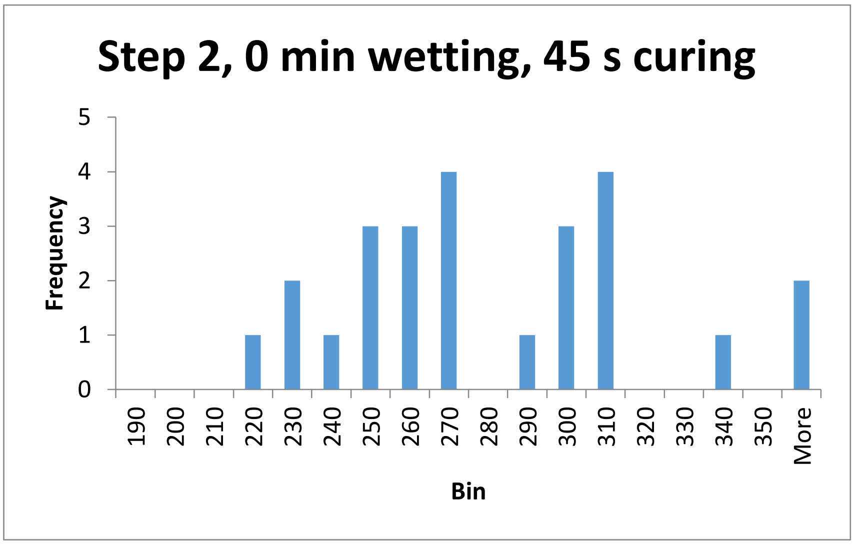


Figure 5.23. Histogram of the push-out forces when LENSES have been bonded to LENS HOLDERS using 32 mg Photobond adhesive and cured for 45 seconds with 0 minutes of wetting time.

Table 5.13. Statistical parameters for the Histogram in Figure 5.23.

	Value	***Unit***
Mean	277,48	N
STD	41,29	N
5%-percentile	228,26	N

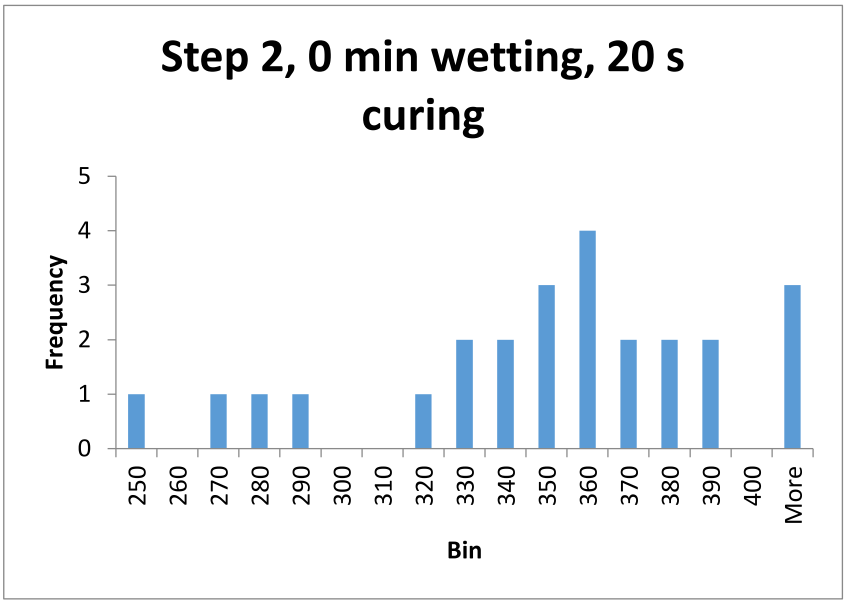


Figure 5.24. Histogram of the push-out forces when LENSES have been bonded to LENS HOLDERS using 32 mg Photobond adhesive and cured for 20 seconds with 0 minutes of wetting time.

Table 5.14. Statistical parameters for the Histogram in Figure 5.24.

	Value	***Unit***
Mean	344,72	N
STD	44,54	N
5%-percentile	262,46	N

When bonding the lens to the holder with photobond, a higher curing intensity than previously was used due to the equipment at hand. The 25 samples cured for 45 seconds generated acceptable results equal to the results seen today. From previous, undocumented tests observations where made that photobond, when cured with high intensity and for a longer time showed signs of becoming brittle, the curing time was reduced to 20 seconds for 25 lenses. The results points to the theory that photobond have the tendency to be over cured, since the mean push-out force increased while the variation was unchanged.

5.5.3 Step 3 using Photobond

The automated robot system was used for dispensing photobond for bonding in step 3. 17 ml was dispensed in each cup, measured to 29 mg in each cup. Different curing times and wetting times were used, see **Appendix B**. Table 5.15 shows the statistical results for all the tests for step 3 while Figure 5.25 and Figure 5.26 show how the push out forces were distributed for the two last series.

Table 5.15. Statistical parameters for the tests carried out using photobond for Step 3.

Test parts	***10***	***10***	***10***	***25***	***15***	
Curing time	10	10	20	20	20	seconds
Wetting	0	5	0	5	3	minutes
UV-intensity	400	400	400	400	400	mW
		Push out values				
Mean	69,4	146,5	159,5	264,0	265,7	N
STD	21,0	26,1	32,3	23,8	18,0	N
5%-percentile	36,5	115,8	113,2	231,5	237,8	N

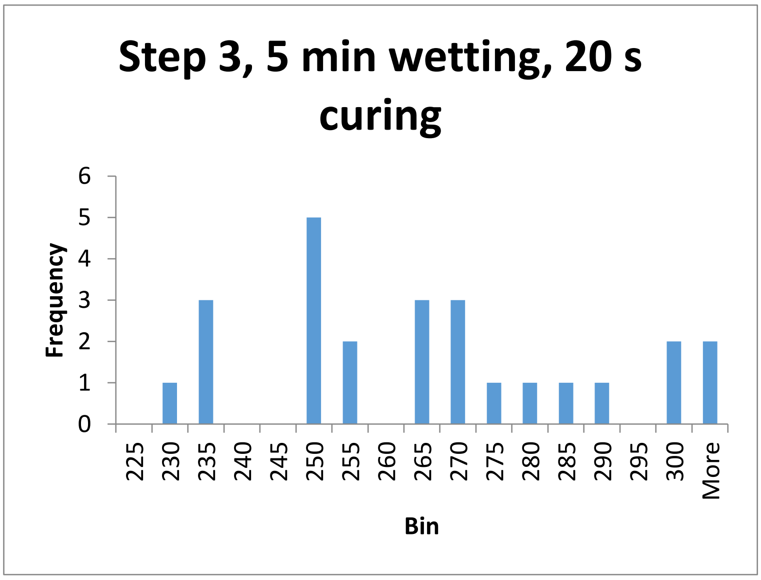


Figure 5.25. Histogram of push out forces for step 3 using photobond, 5 min wetting and curing for 20 seconds.

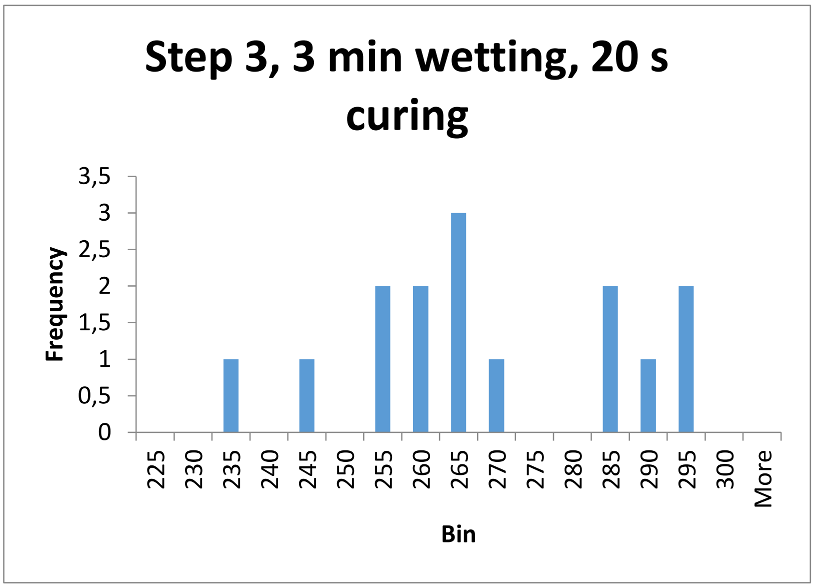


Figure 5.26. Histogram of push out forces for step 3 using photobond, 3 min wetting and curing for 20 seconds.

From the tests in stage 3 using Photobond it became even more evident that the curing parameters and wetting are connected. In the current IBAS process, the Optics and PCB Ass are mated, resulting in the pins are set into the adhesive filled cups. The IBAS sequence today takes roughly three minutes before the adhesive is bonded. Hence, the tests where the adhesive was cured directly after mating the Optics to The PCB Ass is more of adhesive evaluation interest.

As for step 1, the influence of wetting decrease when the curing time increase. Curing for 20 seconds without wetting time generated equivalent results as curing for 10 seconds after 5 minutes of wetting time. When the parts where let too wet for 5 minutes and cured for 20 seconds, stable and high results were acquired. From the last test it was seen that 3 minutes of wetting is more than enough for a sufficient bond, generating the same results as for 5 minutes of wetting and curing for 20 seconds.

The tests show photobond is more sensitive when it comes to wetting, curing time and UV-intensity compared to OP 67. OP 67 seems only to have a lower limit of energy needed (UV-intensity and time) and if an excessive amount of UV-intensity or time is used no visible changes happens to the adhesive. Photobond have both a low and a high limit. If not enough energy is “put into the system” the bond does not build up enough strength. If too much energy is added the adhesive becomes brittle and the bond weak. Also for step 1 and 3. Tendencies of over curing the adhesive was seen for step 2 when using Photobond and also in none recorded tests for step 1. The UV-intensity is different for all the steps due to the equipment at hand making it hard to compare the different curing configurations. In theory, the intensity and time dictates the energy input for curing the adhesive, where time multiplied by intensity gives the energy input in joules. When doing this, it becomes clear that curing energy between 8-13 Joules generated the best results. A quick test, where three optical (step 3) units were cured with 13 J (600 mW, 20 seconds) generated the same result as the tests seen in Figure 5.25 and Figure 5.26 where 8 J was used. The equipment used for Step 3 is the most exact when it comes to measuring the UV-intensity. For step 1 and 2, the variation in intensity might result in a lower energy input than the measured.

Table 5.16. Curing energy used for the tests using photobond. The bold values are the ones that generated the highest and most stable push out values.

	Step 1	***Step 2***	***Step 3***	***Unit***
Configuration 1	6	**13**	4	J
Configuration 2	**13,5**	29,25	**8**	J

Closer analyzing the adhesives when cured it seems that the internal strength of photobond is greater than OP 67. In **Appendix C** there are two samples, one bonded with photobond and the other with OP 67 with the same push-out forces. The sample bonded with OP 67 show clear traces of adhesive on the PCB while for photobond the adhesive is either on the PCB or the cup. The fact that roughly the same force was need for the push-out indicates that photobond have a greater internal strength than OP 67.

6 Analysis

From all the steps, using both adhesives, stable and semi stable results were obtained. In step 1, the best results were achieved using OP 67 where the sixth sigma is 155 N. The use of six Sigmas for a stable process is quite extreme, and the use of three is in this case and by Axis considered good enough due to the theoretical yield of 99,7%. In Table 6.1 the lower limit if Sigma level three is to be used and the actual sigma level is presented for the best test for each step regarding both adhesives.

Table 6.1. Sigma levels and statistical values for the best tests for each step and each adhesive.

Step	*Adhesive*	*Mean*	*STD*	*Sigma lvl 3*	*Current limit*	*Sigma lvl*
1	OP 67	187,94	5,37	171,83	100	16
1	PB	179,89	19,05	122,74	100	4
2	OP 67	221,56	26,69	141,49	170	2
2	PB	344	44,54	210,38	170	4
3	PB	264	23,8	192,6	200	2

For step 1, both adhesives qualify for the tree sigma rule, where for step 2 Photobond performed at sigma level 4. It has however been seen in the current production that OP 67 can be used with great results, and with some fine tuning of the dispenser and curing set-up better results can be expected. When photobond is used in step 3 it reaches sigma level 2 but is close to the higher limit. With some fine tuning of the curing it is likely that sigma level 3 can be reached. The fact that Photobond can be introduced with low sigma levels implies that OP 67 should be replaced.

Further benefits from switching adhesive is the safety aspects for the operators. Reducing the risks in the production demonstrates a willingness to increase cooperation between Axis and the EMS and builds a deeper relationship. The effects of the deeper relationship can only be speculated in, but with increasing global health awareness, it is a wise move to make.

If a new dispenser is to be introduced, the process should be altered in three stages. If the automated dispenser is introduced the dispenser stability is so high that the weighing of the parts can be removed. Instead, samples are weighed when adhesive tubes or needles are changed to recalibrate the dispenser. Hence, scrapping due to excessive or insufficient adhesive amount can be eliminated. With the dispenser, adhesive waste can be reduced to an estimated 0,01 mg/s (test shot) and the tubes are used to 95%. For the first month, the same push-out frequency should be kept to gather data. The yield from push-out tests are expected to be reduced but for calculations the yield is kept at the same as for all three steps

After the dispenser has been implemented, the process have been optimized and a stable process is achieved, the push-out frequency can be reduced. If two units per shift are tested, the test frequency will be 0,9%, 1,2% and 2,4% based on current demand, further decreasing the product cost. The final step is to completely remove the push-out tests.

The tests in the thesis have shown that if the process is controlled the variations in the process can greatly be reduced. The possible cost reductions are presented in Table 6.2, where also OP 67 is compared to Photobond. Table 6.3 show how the cost is distributed over the cost drivers previously discussed for a Hedwig camera.

Table 6.2. Product cost reduction during the 3 improvement stages when the automated system is introduced.

Improvement stage	***OP 67***	***Photobond***
Current production	100%	97%
1	96%	95%
2	91%	90%
3	88%	87%

Table 6.3. Product cost distributed over the ingoing cost drivers for the fully developed process and the current calculated for both adhesives.

	Current stage		***Improvement stage 3***	
Category:	**OP 67**	**PB**	**OP 67**	**PB**
Material (k_b)	79,1%	80,5%	90,2%	91,1%
Adhesive cost (k_{ba})	5,4%	3,7%	2,9%	2,0%
Operator (k_d)	3,6%	3,7%	4,1%	4,2%
Push-out test	6,8%	6,9%	0,0%	0,0%
Machine (k_{cs} and k_{cp})	*1,3%*	1,3%	2,7%	2,8%
Yield Cost	3,8%	3,9%	0,0%	0,0%

The final process will greatly decrease the product cost but also how the cost is distributed. Earlier the machine cost was such a small part of the total cost that cycle time reduction was not prioritized. With the new process, the cycle time affect the total cost more, and optimization of the dispenser is beginning to be more interesting. The final process will save estimated 13% on the OPTICAL MODULE.

Evaluating and implementing a process are two different things. In the lab at Axis the automated system have been evaluated by one operator who is trained to use the system. To be able to implement the system in live production at the EMS, all the results gathered need to be packaged in such a way that it easily can be implemented regardless of the EMS. The main aspects to be considered are high utilization, ease of use, and stability when the process is to be designed.

From the tests it have been seen that the systems variability in dispensed amount increase when the time between use increase. Hence, a high utilization increase the stability of the system. The investment for a system is also distributed over a greater amount of products with increase in utilization. To increase the utilization with current demand levels, one dispenser must be used for several products, where fixtures and programs are easily changed.

Parameters affecting the dispensed adhesive amount are; needle size, pressure, time (in this case speed) and adhesive. Since the needle have an evident effect on the process stability, it is not recommended to switch needle for different programs. Also, the system becomes more difficult to use if the operator have to change or adjust the machine every time the system is to be used. A 20-gage tapered plastic needle have been successfully used for the evaluation of the dispenser. If the cycle time proves to be important to reduce, an 18-gage needle can be used instead. For the tests 30 ml adhesive tubes have been used. To decrease the influence of tube and needle, larger tubes can be used instead. To compensate for pressure build-up in the tube during dispensing, the test shot sequence can be utilized. At the beginning of the program a small amount of adhesive is dispensed on a surface, building up pressure in the tube and making sure that no excess adhesive is dripping or the adhesive is not filling the entire needle at start.

When needle or tube is switched, programs can be recalibrated by either changing speed, pressure or both. Changing pressure will not affect the cycle time but since the relationship between speed and pressure is not linear the adjusted pressure may be correct for one program but wrong for another. Keeping the pressure and adjusting the dispensing speed for each individual program generate more accurate results. However, adjusting each individual speed is more difficult, and also increase the risk of error. From the tests, it was clear that the amount adhesive was not as critical as the placement or curing of the adhesive. Hence a small variation in adhesive amount is acceptable as long as precision and curing is controlled. Regarding this the easiest way to adjust the system is by adjusting the pressure. Suggested is that Axis train a number of people at each EMS that are responsible for calibration of the system.

To design the process for ease of use, the number of steps the operator need to do should be minimized in order to reduce the chance of errors and increase utilization. The process should be designed in such a manner that the operator, with minimal training can operate the system. To achieve this Axis should create, test and verify the programs for every product, deliver and install them at the EMS. The EMS should not change anything in the program without Axis approval, only the pressure should be adjusted.

A simple method to design the process for ease of use is to use individual fixtures for each product where the program is connected to the fixture. For every program, there is a specific fixture marked with a QR code. The operator scans the QR code using a bar code scanner which selects the correct program for the system. The operator then place the fixture in the system and start the dispensing. When the dispensing is finished the operator removes the fixture and cures the adhesive. Figure 6.2 show a possible configuration of the new process. Depending on the EMS the flowchart may take a different form.

The robotic system makes it possible to go from single unit production to batch production for step 1 and 2. Figure 6.1 show an example of how a fixture for 5 lenses can be designed. A similar fixture is used today but with only room for one lens. The use of two fixtures and balancing the dispensing program after the time it takes to load the fixture the cycle time for a batch can be reduced.

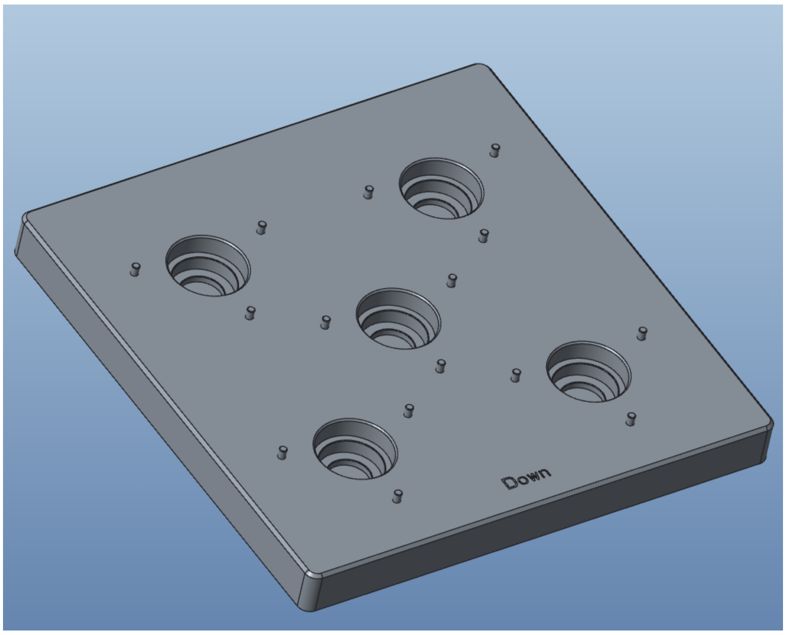


Figure 6.1. Fixture for dispensing adhesive on 5 lenses in one fixture

How the PU yield is affected by the automated system is too early to tell and needs to be further investigated over a longer period. The expectation is that the infinite focus problems and corner focus problems that are today are likely to decrease due to the compensation for shrinkage can be better adjusted. To fully analyze the impact of the automatic dispenser on the optical module, data from production needs to be gathered over a longer time. When units fail the PU-tests, closer examinations of the units need to be performed for future reference and information for finding the source of the failure.

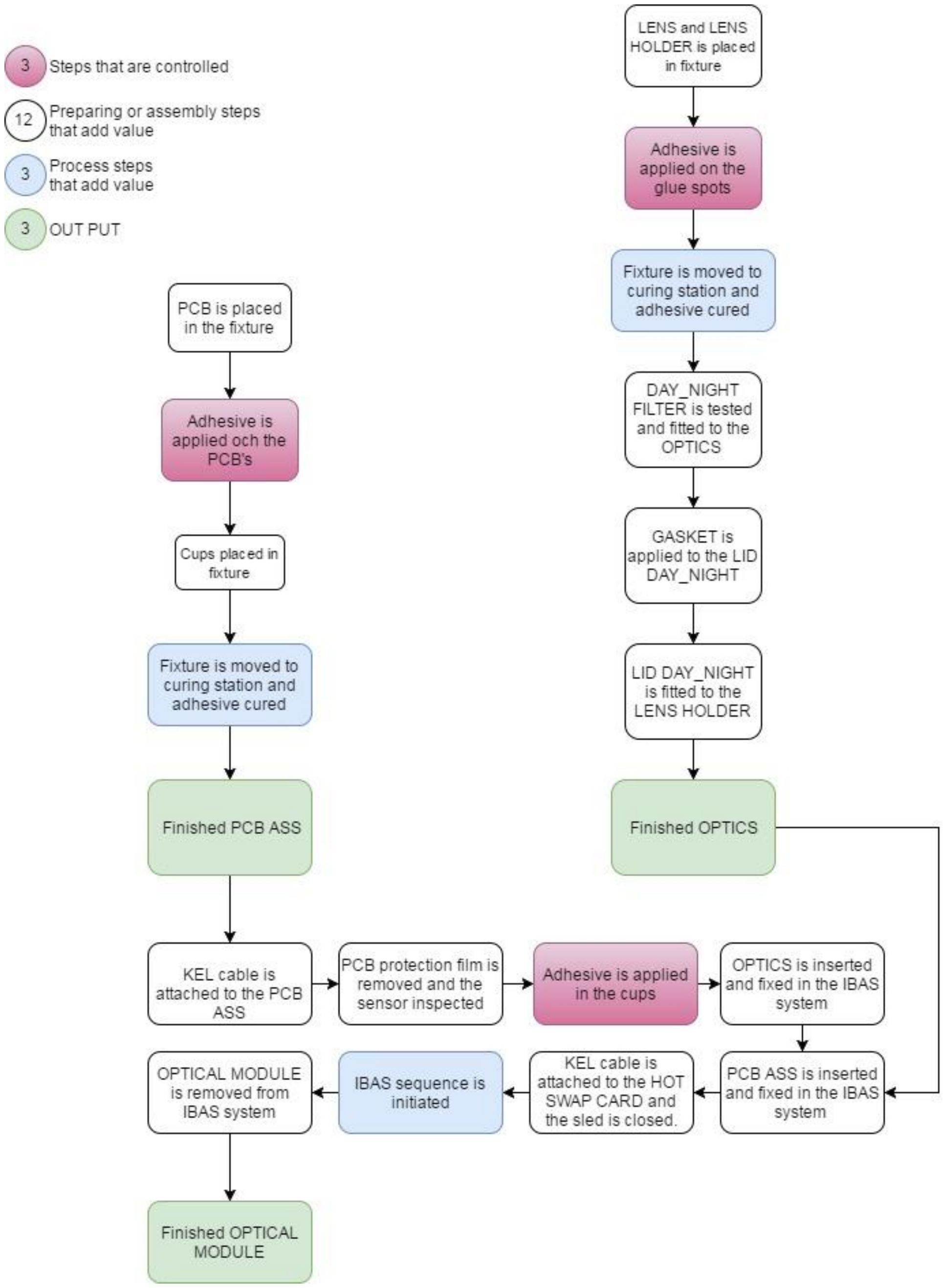


Figure 6.2. Possible flowchart of the developed process using the automated dispensing system. The number of process steps can greatly be reduced.

7 Discussion

During the testing phase a pragmatic approach was taken, where good enough results was sought. Due to the approach, no optimized parameters have been deduced. The importance of optimization is however at this point not of interest since the dispenser later need to be fitted into the current production line and optimized with the line.

The influence of curing was found to have a greater impact on the adhesive bond than previously expected. During tests, UV intensity have both been controlled and measured in those cases where it was needed. Due to this the uncertainty of the curing was reduced and clear results showed that curing time and intensity have great impact on the process. The concept of defining the curing as energy input needed is interesting to analyze deeper. If an energy dose can be defined, for example that 10-13 J is needed to cure the adhesive, each EMS can individually balance curing time to the rest of the line. Further test with different curing times and intensities were never made due to a lack of time and as discussed above, good enough results were already found.

Regarding step 1, in many cases the cups broke during push-out tests, resulting in an uncertainty of the strength of the bond. When the cups broke, the mean and standard deviation became lower, making the different tests more difficult to analyze. The maximum value of the bond is not that important, since the push-out test is carried out to see if the process is done correctly. By modifying the forces exceeding 190 N, better data was obtained to compare the different adhesives and process parameters. This however will generate lower standard deviations for tests with high extreme values since only the lower part of the distributed data is analyzed. Since the important part is to see the lower limits, the method of altering the data is considered okay.

The push-out tests were carried out using the same fixtures and methods used at the EMS which generates more realistic and comparable results. The limits on the other hand might be adjusted if push-out tests are to be used for process validation. In the camera, the PCB is suspended by the pin/cup bond from step 3. The PCB A weighs roughly 5 g and the push out limit for a cup is 100 N. For a cup to be exposed to forces in the vicinity of 100 N, the PCB needs to be exposed to roughly 2000 G forces. Due to the design, a minimum of two bonded spots on the same side of a PCB needs to fail for the PCB to be able to move in a finished camera, which is highly unlikely according to the push-out history over the past months. The housing of the camera also protects the optical module, absorbing the main part of the force when the camera is exposed to violence. The limits used today are very high, but due to the push out history and the thesis tests showing that the limits can be reach with a correctly designed process it might be better to completely remove the tests, and trusting the automated system instead. Even if the limits are kept at the current values, the testing with the automated system show sigma levels high enough to statistically prove that the process is stable enough for the removal of the push out tests. The main aspects of the adhesive bond is stability, the maximum force is of less importance.

Regarding the push-out tests used today the uncertainty of the test due to the variable process leaves much to offer. Since adhesive dispensing is operator dependent there is no guarantee that the operator puts adhesive in all areas every time. Unless a unit happens to be among that 1% tested in push out, the possible problems on that unit will not be detected before PU-tests. The units that are tested are destroyed and hence units that pass the tests are scrapped anyway. If push out tests are to be used in the future, the tested unit should be logged and the push out value should be compared to the amount adhesive on that unit. As it is today, the push out value is logged but not compared to the adhesive amount. If both force and amount was logged, it could be established if there is any correlation between adhesive weight and push out force. If there is none, the adhesive weight limit can be lowered. This form of data can later be used for further development in the adhesive process.

It is however a difference between controlled testing and high volume production. During the first stages of high volume production using the automated system, push out tests are necessary to fully evaluate the process. With a more reliable process, push out tests could be reduced to only be performed at the beginning of every shift. The push out tests will also tell more about the process since the parameters that affect the bond will be better controlled.

From the results, it becomes evident that Axis pays much more for push out tests than they should. Axis is responsible to know what data is accessible and look after its own interests. The data used in this comparison is accessible from the EMS but is not used by them for anything because they are not required to do so. It is acceptable to use estimates at the beginning of a product life cycle since there is nothing else to base calculations on but Axis should require their partners to base later updates to the quotation on historic data when available.

Non-value adding activities in each process step such as weight control could be eliminated. Of course, validation of the process must take place to some extent, but with a better controlled process the frequency of validation can be reduced, lowering the cycle time for a batch as a result. When a push out test is being performed, the operator stops production to perform the test, which also result in an increase in cycle time. The UV oven used for step 3 does not add anything to the process. If the adhesive is cured before going into the oven, nothing changes and the extra cycle time is a pure waste. If the adhesive is not cured, it is very likely that the positioning of lens relative to the sensor change when the unit is handled, later curing the parts in the wrong position. Focus should be on finding the right parameters for the initial curing in IBAS, designing the parts and process in a manner that allows repeatable and easy curing.

From the production history, obvious error data, for example adhesive weights of 200 mg when mean is 10 mg have been sorted out. The sortation in data may affect the results in a positive way. Some of the deleted data might actually be correct production data, but have been so off that it was mistaken for error data. The results from this is that the production seems to be better than I actually is. Of course there the opposite case, where error data have not been sorted out, making the process seem worse than it actually is. The amount of data used is considered to be great enough to absorb the sortation, since less than 1% have been sorted out.

When analyzing the data, it became obvious in some cases that data have been modified. From the adhesive weight log in step 3, 100 % of 17 000 units are within the set limits. The probability that 100% of the units pass is unlikely and when compared to step 1 and 2, where the yield is roughly 96% it became evident that values had been changed. From the visit to the EMS it became more obvious that units passed controls with too much adhesive on them. From the adhesive tests the amount adhesive have small effect on the adhesive bond due to the extreme overcompensation in amount due to the low precision and high variability. But when the EMS alter values to show a better production than in reality, other questions begin to rise, for example if anything else is altered.

Analyzing the costs related to the optical module is not easy due to many of the costs related to this process are not measured in detail. The major reason for this is that Axis doesn’t own the EMS and thus do not have control over all aspects of production economics. The two partners negotiate and agree on a price for the product. Costs are consequently known on a product level but the visibility is poor as to where value is added and what improvements to the processes will generate largest cost reduction. As Axis can contribute to making the assembly process easier and faster, it should work as grounds to renegotiate a lower price point. Axis works closely together with its partners to ensure quality and help develop production processes which have made it possible to at least find a good enough estimate for many parameters in the cost break down. IBAS, which is lent out to the manufacturers, is a prime example of an effort to assist with equipment and knowledge to enable partnering EMS to deliver products with desired quality and function.

Due to lack of detail about costs on other than product level, several parameters used in the MCBD have been calculated based on unofficial or previously unused data. Costs related to floor space for the stations, energy usage and machine cost for other than IBAS is by the EMS applied on the final product as overhead which is not brought up in the model. Because the applicable share of the cost to be carried by the optical module is not available and can only be guessed, it has been left out. Operator cost per hour is not official information but is based on priory used figures at Axis. Cost of material was taken from Axis but it was found that part cost is valued different at EMS. It is likely because Axis only have access to target prices for parts that are not sourced and distributed to the EMS through their own company. Because yield has not officially been measured in the dispensing process before it is probably not representing exactly how the EMS values cost of rejects. With these factors in mind the total cost calculated by the model will differ from the valuation at the EMS to some extent. The total value presented in the model should not be taken as absolute. Its aim has always been to use available data and observations to give the user an idea of what the true cost should be in each category. In the case of adhesive dispensing and push-out test which have been the main focus and put in to context with other cost parameters. It could be argued that cost parameters left constant in the model should have rather been left out. This was discussed among the authors and a decision was made to leave them included to give a sense of how all cost categories are valued in in relation to each other and what areas to focus efforts on.

To make it easier to achieve a more accurate cost analysis of this sort there are several parameters needed to be improved. The First is to make sure costs presented by the EMS are accurate and based on historic data rather than standard calculations. Push out test cost mentioned earlier being evidence of such a case where Axis pays more money than needed because parameters behind the calculation have not been verified before approval.

Secondly, performed data analysis of the process proves there should exist rejects in at least step 1 and 2 of the assembly process due to adhesive weight variations and push out tests. As this type of data is not used, yield in final PU-tests for the camera will give a misleading representation of reality. The actual yield is in fact lower than what is presented. To overcome this issue, yield for each individual process step should be measured. By measuring the yield at a lower level the problems in the process becomes more apparent, resulting in a better understanding of the process and where future development work is needed. By measuring the yield at different stages, process cost calculations can be made for each planning point generating a better view over the process.

8 Conclusion

If used correctly, the automated dispensing system can generate stable, predictable results which will decrease the amount of adhesive used due to the increase in precision. The high precision also increased the repeatability of the process, rendering push out test obsolete. The weighing of the adhesive can also be removed due to better control of the dispensing. The testing showed that the curing and wetting had a big impact on the adhesive bond, while the contaminate present on the parts and adhesive amount had little or none influence. Photobond can with the right curing parameters replace OP 67 with as good or better results, making the process safer and the product cheaper.

An automatic dispensing system will generate a smoother, safer and cheaper process where the error sources are less, increasing the product quality. By implementing the system, many factors improve, while also enabling production of more advanced products in the future.

With a better controlled dispensing and curing process, the push-out testes can be reduced and eventually completely removed, lowering the module cost by up to 13%. The savings will result in a payback time on the automated dispenser used for the tests in less than 1 year, if the dispenser was only used for the Hedwig camera. Using the dispenser for several different products, which is easily done, would generate a much shorter payback time.

9 Recommendation

If Axis wants to continue their product development in the current direction, the use of an automated dispensing system offers many advantages in both production quality and cost reduction. The author's recommendations are;

- Invest in an automated dispensing system which will reduce many of the variables in the process making it easier, safer and cheaper

- Use the Hedwig camera as a pilot project, fully deploying the cost reduction development discussed in the thesis and continuously follow up the on process using the data for further development.

- Standardized method of collecting and analyzing how the yield for each step in the production arise. Start measuring throughput for each step instead of just using PU-test as yield measurement.

- Follow up production parameters and history. Use the data for future cost calculations and price negotiations with the EMS. Simple methods of analyzing the data is presented in the thesis.

- The model derived in the thesis can be used for future products, analyzing where cost drivers arise and how they affect the product cost.

9.1 Areas for further investigation

Further investigations in process parameters for Photobond needs to be analyzed to be able to fully implement the adhesive generating the same result as for OP 67. Tests have shown that it is fully possible to achieve as good or better results with Photobond, but as of now with higher variations due to the uncertainty of the adhesives characteristics. The variations in push-out forces might be connected to the curing time and intensity and is hence the first area for further investigations. A full analysis of the connection will give a better base for future projects and camera development, reducing sources of errors in the current production. If adhesive is to be used in the future, a deeper understanding is necessary if cost savings are of interest. With a deeper understanding, push-out tests and quality losses connected to the adhesive can be reduced.

Better backtracking of cost drivers in the production and a standardized method of obtaining, analyzing and using production history for future cost reduction work needs to be investigated. The model derived can works as a tool to analyze where cost arise and how they affect the product cost.

10 References

[1] T. Elfström, Interviewee, *DFA-engineer.* [Interview]. 18 01 2016.

[2] A. Higgins, "Adhesive bonding of aircraft structures," *International Journal of Adhesion and Adhesives,* vol. 20, no. 5, pp. 367-376, 2000.

[3] L. Grant, "Experimental and numerical analysis of single-lap joints for the automotive industry," *International Journal of Adhesion and Adhesives,* vol. 29, no. 4, pp. 405-413, 2009.

[4] A. Kinloch, Adhesion and Adhesives: Science and technology, London: Chapman and Hall, 1987.

[5] R. Adams, Adhesive bonding; Science, technology and applications, Cambridge: Woodhead Publishing Limited, 2005.

[6] J. Fink, REACTIVE POLYMERS FUNDAMENATLS AND APPLICATIONS, Oxford: Elsevier Inc, 2013.

[7] K.-Y. Z. H. Law, Surface Wetting: Characterization, Contact angle, and fundamentals, Richmond: Springer, 2016.

[8] U. Vazquez, "Calculating the surface tension between a flat solid and a liquid: a theoretical and computer simulation study of three topologically different methods," Springer, Richmond, 2008.

[9] J. Chen, "Molecular Dynamics Simulations for Predicting Surface Wetting," *AIMS Materials Science,* vol. 1, no. 2, pp. 121-131, 2014.

[10] H. Z. W. Fox, "W.A. POLYTETRAFLUOROETHYLENE, THE SPREADING OF LIQUIDS ON LOW ENERGY SURFACES. I.," Naval Reaserch Laboratory, Washington D.C., 1950.

[11] H. Z. W. Fox, "THE SPREADING OF LIQUIDS ON LOW-ENERGY SURFACES. III. HYDROCARBON SURFACES," Naval Reasarch Laboratory, Washington D.C., 1952.

[12] S. Siboni, "The solid surface free energy calculation II. The limits of the Zisman and of the “equation-of-state” approaches," *Journal of Colloid and Interface Science,* vol. 27, no. 1, pp. 454-472, 2004.

[13] J. Dann, "Forces involved in the adhesive process: I. Critical surface tensions of polymeric solids as determined with polar liquids," *Journal of Colloid and Interface Science,* vol. 32, no. 2, pp. 302-320, 1970.

[14] H. J. Z. J. Mengnan Q, "Superhydrophobicity, Learn from the Lotus Leaf," in *Biomimetics Learning from Nature,* Reijka, InTech, 2010, pp. 326-342.

[15] X. Z. M. J. D. L. J. C. L. Ye, "Transition of super-hydrophobic states of droplet on rough surface," Springer, Berlin, 2010.

[16] J. Zhi-hai, "Dynamic properties of vibrated drops on a superhydrophobic patterned surface," *Applied Thermal Engineering,* vol. 62, no. 1, pp. 507-512, 2014.

[17] F. Tabor, "The direct measurment of normal and retarded van der Waals forces," *Proc. Roy. Soc,* vol. 312, no. 11, pp. 435-450, 1969.

[18] F. I. J. Tabor, "The Measurement of Van Der Waals Dispersion Forces in the Range 1.5 to 130 nm," *Proc. Roy. Soc.,* vol. 331, no. 1, pp. 19-38, 1972.

[19] V. Parsegian, Van der Waals Forces: A Handbook for Biologists, Chemists, Engineers, and Physicists, Cambridge: Cambridge University Press , 2010.

[20] R. Patrick, Treatise on ADHESION and ADHESIVES, New York: MARCEL DEKKER, 1981.

[21] M. Bellgran and K. Säfsten, Production Development - Design and development of Production Systems, London: Springer, 2010.

[22] J.-E. Ståhl, Industriella Tillverkningssystem, Del II - Länken mellan teknik och ekonomi, 2 ed., Lund: Industriell Produktion at Lunds Universitet, 2012.

[23] V. A. Tipnis, S. J. Mantel and G. J. Ravignani, Sensitivity Analysis for Macroeconomic and Microeconomic Models of New Manufacturing Processes, Annals of the CIRP, vol. 30, CIRP, 1981, pp. 401-404.

[24] M. Jönsson, C. Andersson and J.-E. Ståhl, A General model for Manufacuring Cost Simulation, Lund: Proceedings of the 41st CIRP Conference on Maufacturing Systems, 2008, pp. 33-38.

[25] P. Fenckner and L. A. Samuelson, Produktkalkyler i industrin, Västervik: Sveriges Mekanförbund, 1984.

[26] R. S. Kaplan and R. Cooper, Cost & Effect: Using Intergrated Cost Systems to Drive Profitability and Performance, Boston, Massachusetts: Harvard Business School Press, 1998.

[27] C. Ax, C. Johansson and H. Kullvén, Den Nya Ekonomistyrningen, 4 ed., Liber, 2009.

[28] M. Javedusen and D. Darshak, "Reducing rejection/rework in pressure die casting process by application of DMAIC methodology of Six Sigma," *International Journal for Quality Research,* vol. 9, no. 4, pp. 577- 604, 2015.

[29] R. Rutka, Interviewee, *Process engineer.* [Interview]. 13 02 2016.

[30] N. Dzinovic, Interviewee, *Part costs.* [Interview]. 16 2 2017.

[31] M. Nyman, Interviewee, *Production System Manager.* [Interview]. 15 March 2017.

[32] H. Molin, Interviewee, *Capacity Planner Deman & Supply at Axis Communications.* [Interview]. 24 04 2017.

[33] "Socratic," 2015 10 7. [Online]. Available: https://socratic.org/questions/how-can-van-der-waals-forces-be-either-attractive-or-repulsive. [Accessed 9 5 2017].

Appendix A

Hedwig production process in the cleanroom can broadly be divided into three main steps; Preparation of the PCB UNIT, Preparation of the OPTICS unit, and bonding of the OPTICAL MODULE. Each of these steps can be broken down to individual activities. The current process is explained below.

Step 1: PCB UNIT

Table 1. Components used for Step 1.

PARTS USED	AMOUNT
PCB	1
INSERT ADHESIVE	4

1. PCB and INSERT ADHESIVE cups are weighed and the scale is tared to 0, 000 so the amount of adhesive applied further on can be measured.
2. The INSERT ADHESIVE cups are placed in a fixture and vacuum is applied to ensure that the cups are fixed.
3. Adhesive is applied on the flange of the INSERT ADHESIVE cups. 5 (+/-1) mg per cup.
4. The PCB is placed in the fixture and aligned with the cups using guiding pins. The lid of the fixture is placed on top using guiding pins and the fixture is closed.
5. The vacuum is released and the whole fixture is moved to a curing station.
   a. The fixture is fixed by a press
   b. UV-lamps cure the adhesive
   c. Fixture is released and PCB removed
6. The PCB is removed from the fixtures and weighed. If the amount of adhesive used in total is 64-94 mg, the PCB is cleared for further assembly.
7. Push-out tests are carried out according to plan.

Table 0.2. Output from step 1.

FINISHED UNIT	AMOUNT
PCB ASS	1

Step 2: OPTICS

Table 3. Components used for step 2.

PARTS USED	AMOUNT
LENS	1
LENS HOLDER	1
DAY_NIGHT FILTER	1

LID DAY_NIGHT	1
GASKET SENSOR	1

1. The LENS and the LENS HOLDER are placed on a scale which is then tared to 0, 0000.
2. The LENS PROTECTION cover is removed from the LENS and saved for later use. The LENS is then placed in a fixture and the LENS HOLDER is placed on top.
3. Adhesive is added in the two adhesive spots. 20 +/- 5 mg in each spot.
4. The fixture is moved to a curing station and vacuum is applied to hold the parts steady.
    a. Fixture is placed into curing station
    b. UV-lamp cure the adhesive
    c. When curing is done the fixture is removed
5. The unit is taken out of the fixture and the LENS PROTECTION is re applied. The unit is weighed and the amount of adhesive used is recorded.
6. Push-out tests are done according to control plan.
7. The DAY_NIGHT FILTER is tested and then applied to the OPTICS.
8. A gasket is applied to the LID DAY_NIGHT unit.
9. Add the LID DAY_NIGHT unit to the OPTICS by snap fitting.

Table 4. Output from step 2

FINISHED UNIT	AMOUNT
OPTICS	1

Step 3: OPTICAL MODULE

Table 5. Components used for step 3.

PARTS USED	AMOUNT
OPTICS	1
PCB ASS	1

1. Attach the KEL cable to the PCB ASS
2. Remove the PROTECTIVE FILM from the SENSOR and the SENSOR is inspected using a microscope and cleaned if necessary.
3. The PCB and KEL cable is weighed and the scale is tared to 0,000.
4. Adhesive is added into the INSERT ADHESIVE cups, 20 +/- 5 mg in each.
5. The PCB ASS and KEL cable is re-weighed and the amount of adhesive used is recorded.

6. If the total amount of adhesive is within the limits the PCB ASS is inserted into the IBAS system. If the IBAS system is not ready the unit is covered with a lid to prevent the adhesive from curing in the visible light.
7. When inserted into the IBAS system the PCB ASS is aligned and vacuum is applied to fixate the PCB.
8. The OPTICS unit is inserted into the IBAS system and fixated.
9. The IBAS system is closed and the KEL cables free end is connected to the card on the lens unit fixture (HOT SWAP CARD).
10. IBAS sequence is run.
11. When the IBAS sequence is finished the vacuum is released, the KEL cables is disconnected from the HOT SWAP CARD and the sled is moved. The OPTICS and PCB ASS units are now bonded into one finished OPTICAL MODULE which is removed and the LENS PROTECTION cover is added. The KEL cable is then removed from the OPTICAL MODULE.
12. The OPTICAL MODULE is placed into a tray. When enough units are in the tray it is moved to a UV oven and cured for 30 seconds.
13. Push out tests are carried out according to plan.

Table 6. Output from step 3.

FINISHED UNIT	AMOUNT
OPTICAL MODULE	1

The OPTICAL MODULE is now done and ready to be assembled into the camera body.

Appendix B

Table 1. Tested parts for stage 1. 7 ml OP 67 weighs 8 mg.

Part	**Volume (ml)**	**Fully exposed adhesive**	**Curing time (s)**	**UV intensity (mW)**	**Number of parts**	**Validation**
INSERTS to PCB RAW	4x7	No	20	600-700	25	Push-out test
INSERTS to PCB RAW	4x7	Yes	20	600-700	25	Push-out test
LENS to HOLDER	10x2	Yes	20	1800-2000	25	Push-out test
INSERTS to PCB A	4x7	Yes	20	600-700	8	Push-out test

Table 2. Tested parts for Delo Photobond, 7 ml Photobond weighs 11.5 mg.

Part	**Volume (ml)**	**Wetting time (min)**	**Curing time (s)**	**UV intensity (mW)**	**Number of parts**	**Validation**
INSERTS to PCB RAW	4x7	0	20	300	10	Push-out test
INSERTS to PCB RAW	4x7	5	20	300	10	Push-out test
INSERTS to PCB RAW	4x7	0	45	300	25	Push-out test
INSERTS to PCB RAW	4x7	5	45	300	25	Push-out test
INSERTS to PCB A	4x7	0	45	300	8	Push-out test
LENS to HOLDER	2x10	0	45	650	25	Push-out test
LENS to HOLDER	2x10	0	20	650	25	Push-out test

OPTICS to PCB Ass	4x17	0	10	400	10	Push-out test
OPTICS to PCB Ass	4x17	5	10	400	10	Push-out test
OPTICS to PCB Ass	4x17	0	20	400	10	Push-out test
OPTICS to PCB Ass	4x17	5	20	400	25	Push-out test
OPTICS to PCB Ass	4x17	3	20	400	15	Push-out test

Appendix C

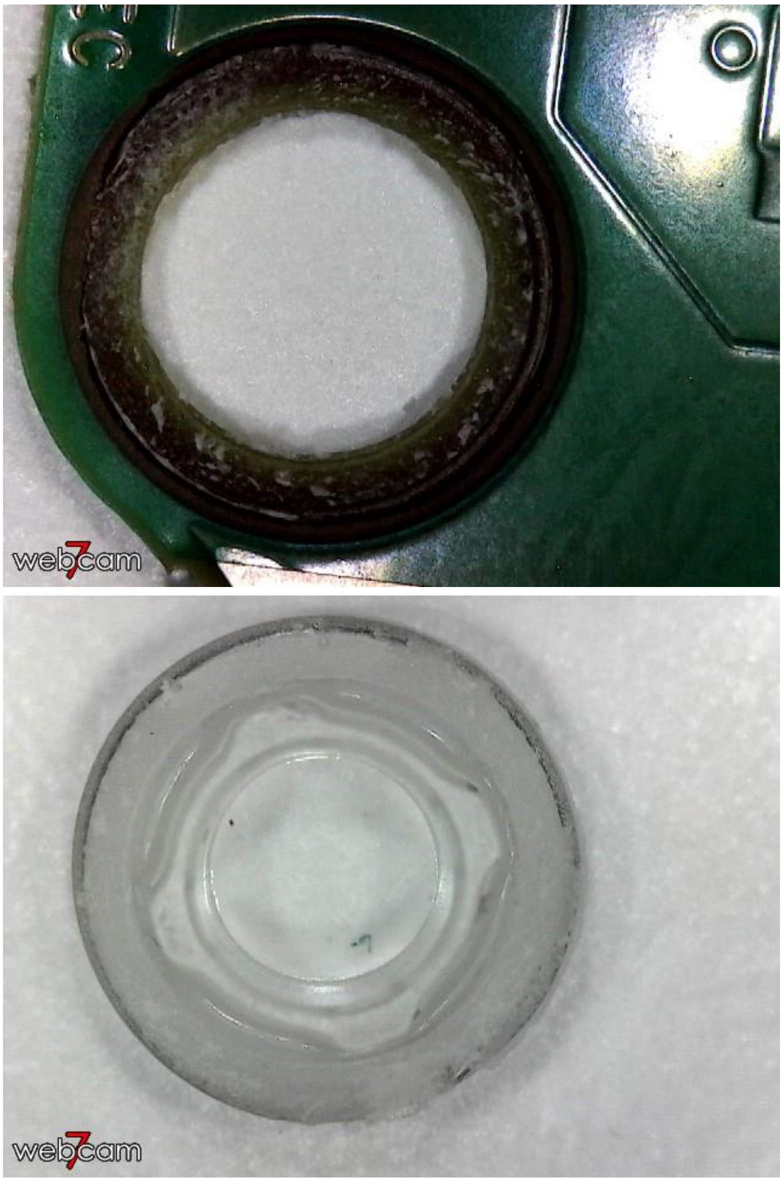


Figure 0.1. Images of INSERT and PCB RAW with a push-out force of 206,7 N. It can be seen that the adhesive have wet the PCB well and there is rests of the adhesive on the PCB. The break is hence inside the adhesive and is considered a cohesive break. Adhesive: Dymax OP 67.

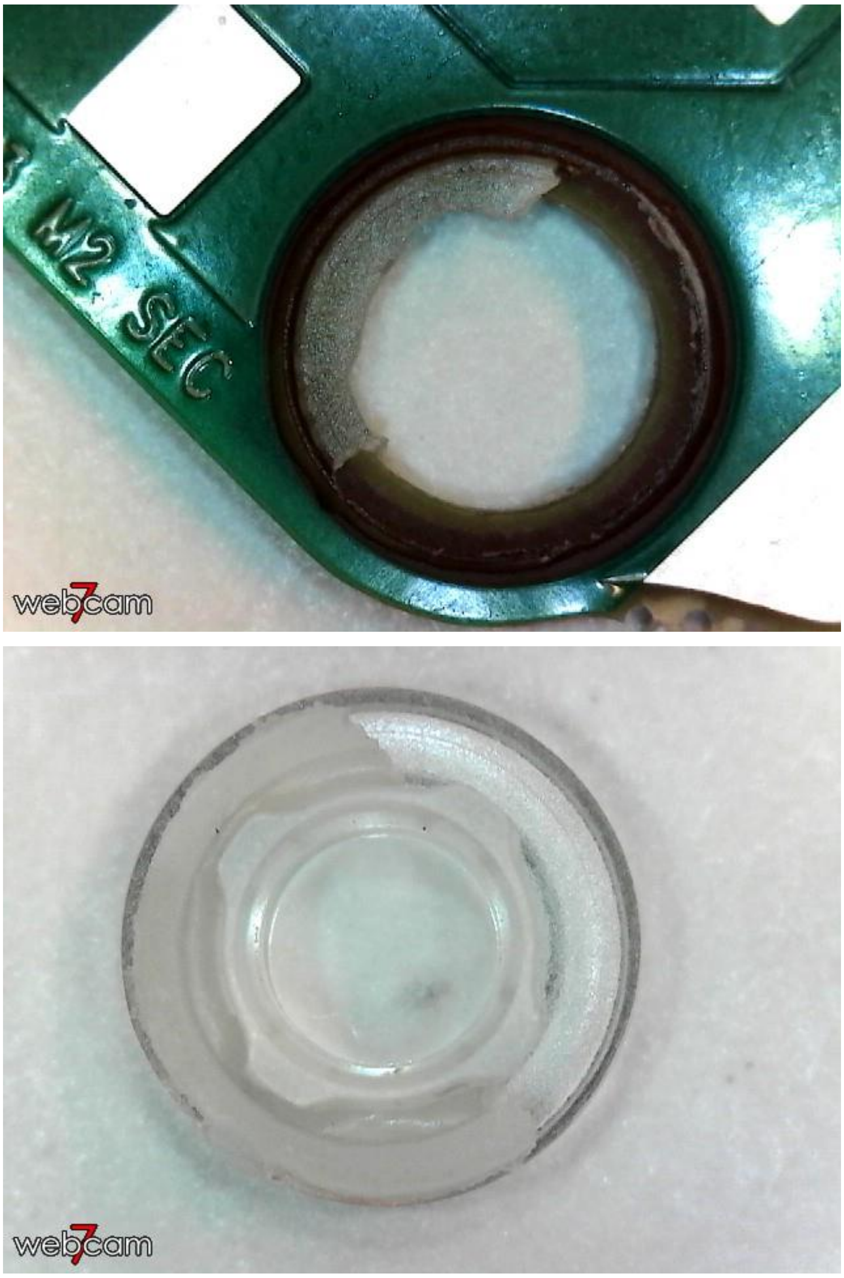


Figure 0.2. Images of INSERT and PCB RAW with a push-out force of 78,5 N. There is no wetting on parts of the PCB, while parts of the INSERT is not wet properly. This can be seen by the adhesive rests on the PCB where a thick, smooth film is present. The break is hence in the interface between the adhesive and parts and is considered an adhesion break. Adhesive: Dymax OP 67.

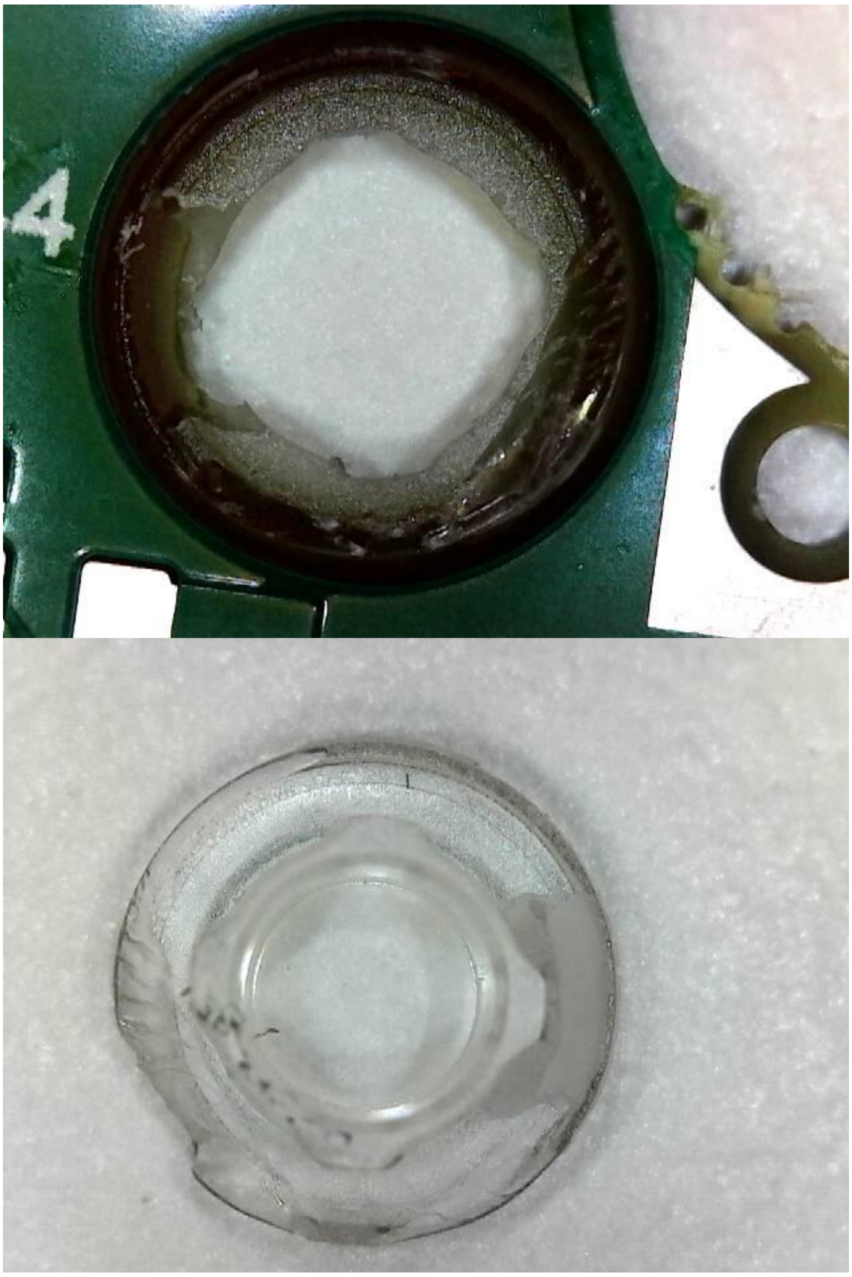


Figure 0.3. Images of INSERT and PCB RAW with a push-out force of 200 N. There are rests of the adhesive on the PCB and on the insert. The insert have also been damaged and a piece of the insert is still stuck to the PCB. The break is both inside the adhesive but mostly in the interface between adhesive and substrate, resulting in an adhesive break. Adhesive: Delo Photobond.

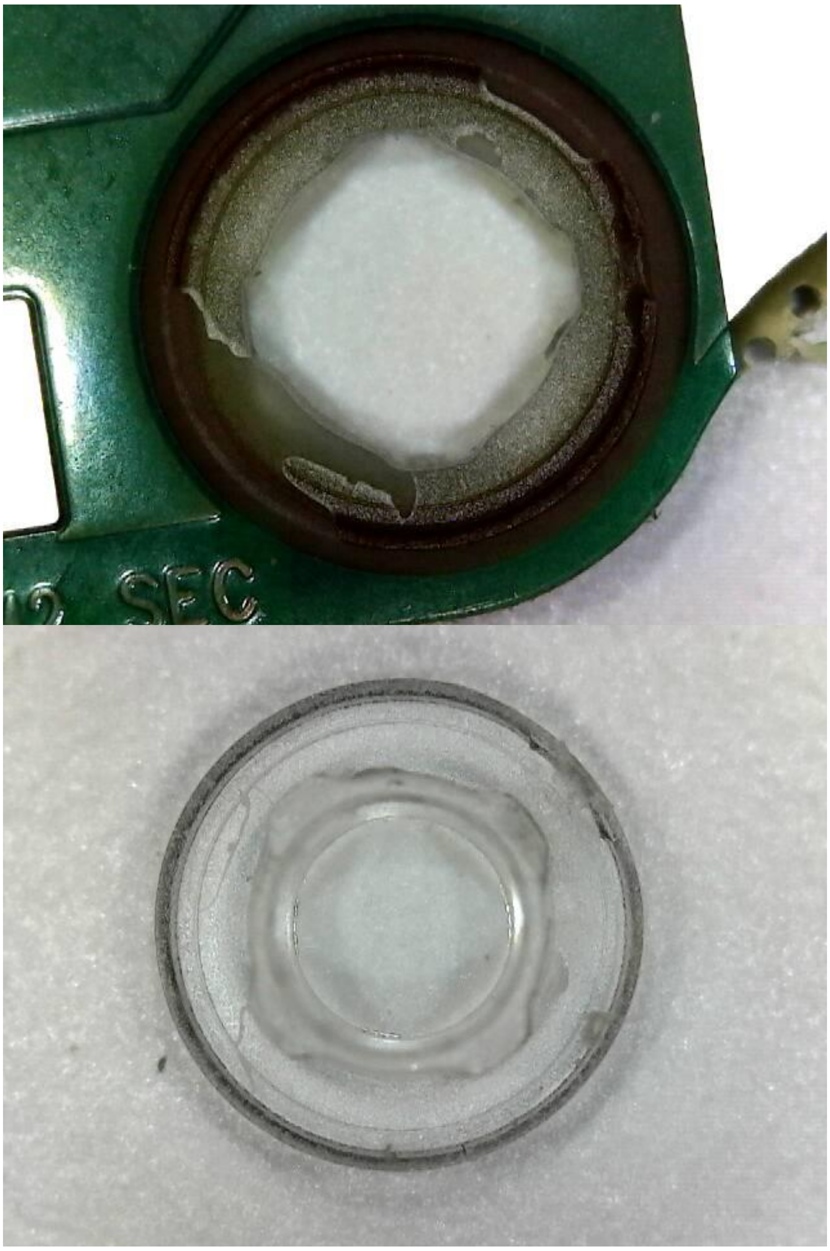


Figure 0.4 Images of INSERT and PCB RAW with a push-out force of 59 N. It can be seen that there is insufficient wetting of the substrates and the adhesive is stuck to one of the parts. There is no sign of adhesive on the insert while there is missing adhesive on the PCB. The cause is probably that the adhesive have not wet the PCB nor the insert and have "fallen off". Adhesive: Delo Photobond.

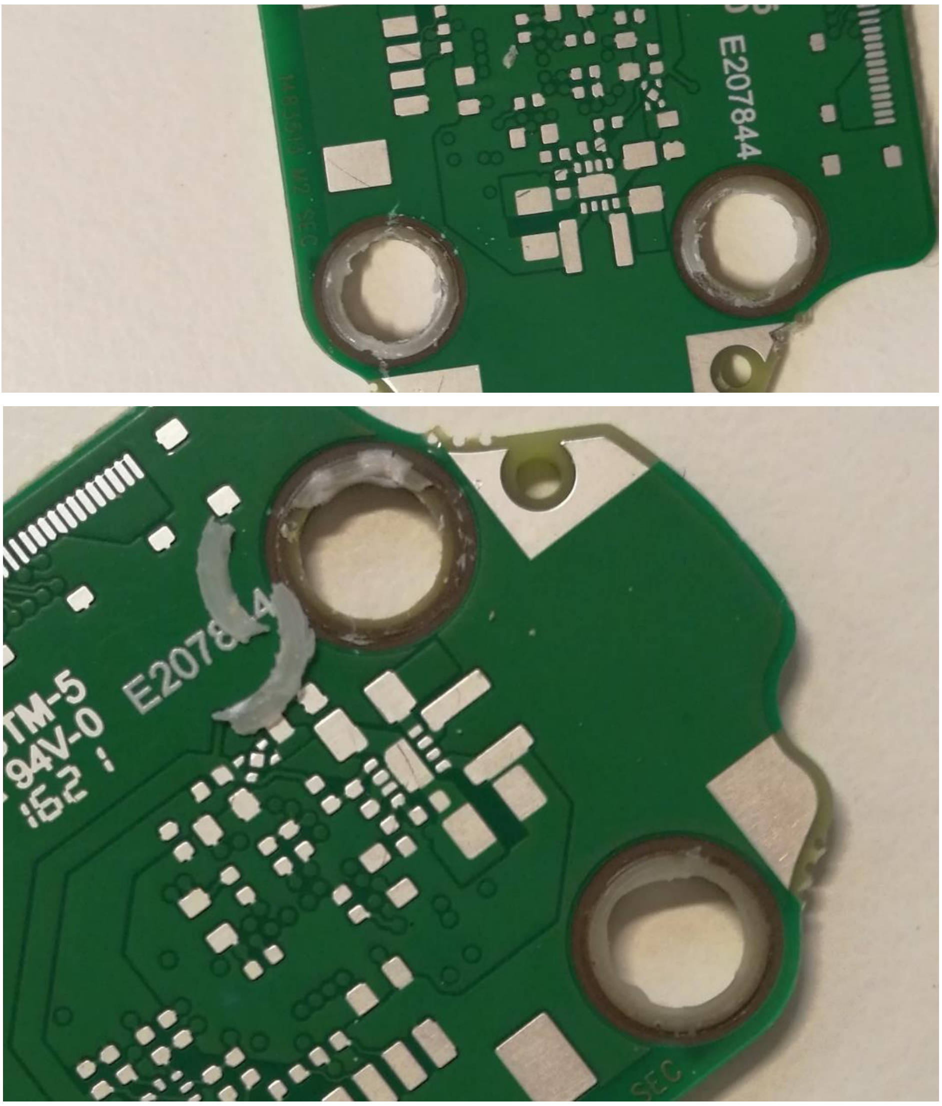


Figure 0.5. Top PCB is 9 mg OP 67 cured openly under a DELOLUX 80 lamp. The adhesive rests are hard and brittle and not easily removed. When tweezers was used the adhesive came off in small pieces, leaving marks seen on the left circle. The bottom PCB is 9 mg OP 67 cured using the current fixture and Panasonic 365 nm UV-lamps. The adhesive have a dull gray color and can quite easily be removed in big pieces.

Appendix D

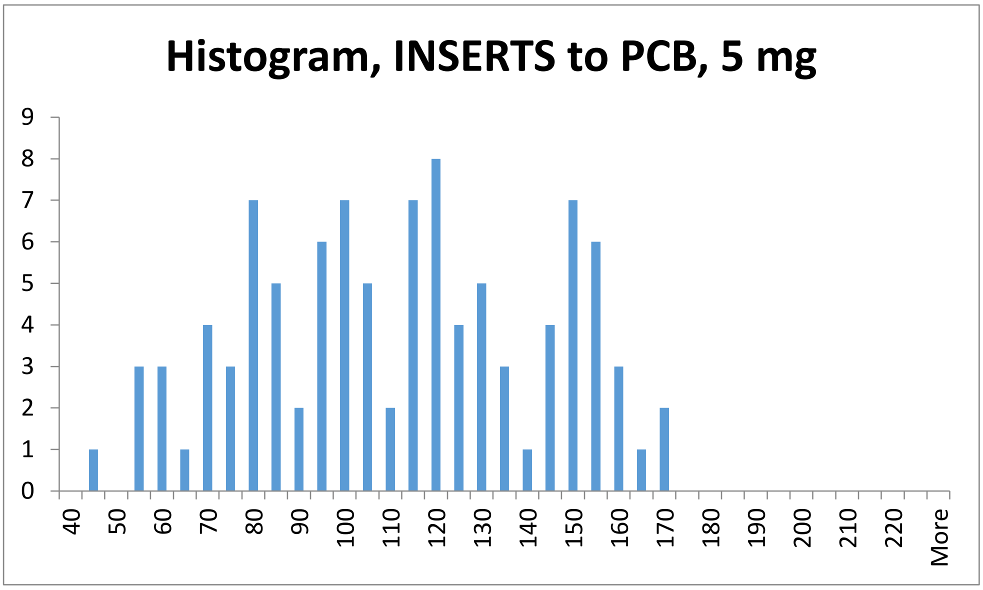


Figure 0.1. Histogram of 100 inserts bonded with 5 mg OP67 adhesive. The tests were carried out by curing the adhesive inside the fixture, but without calibrated and controlled UV-lamps. The results of the test is not reliable but it can be concluded that it is possible to bond cups to a PCB with only 5 mg adhesive and obtaining good results.

Appendix E

Table 1. List of symbols for MCBD model.

k_b	Material cost for one unit
k_{cp}	Hourly machine cost during production
k_{cs}	Hourly machine cost during down time
k_D	Hourly cost for one operator
N	Ture batch size
N_0	Nominal batch size
t_p	Total production time
t_s	Average downtime per unit
t_0	Nominal cycle time
t_{0v}	True cycle time
q_Q	Scrap rate
q_S	Downtime rate
q_P	Cycle time reduction rate
T_{SU}	Set up time
U_{RP}	Production development costs
U_{RB}	Utilization during reduced capacity
T_{pb}	Total production time for a batch