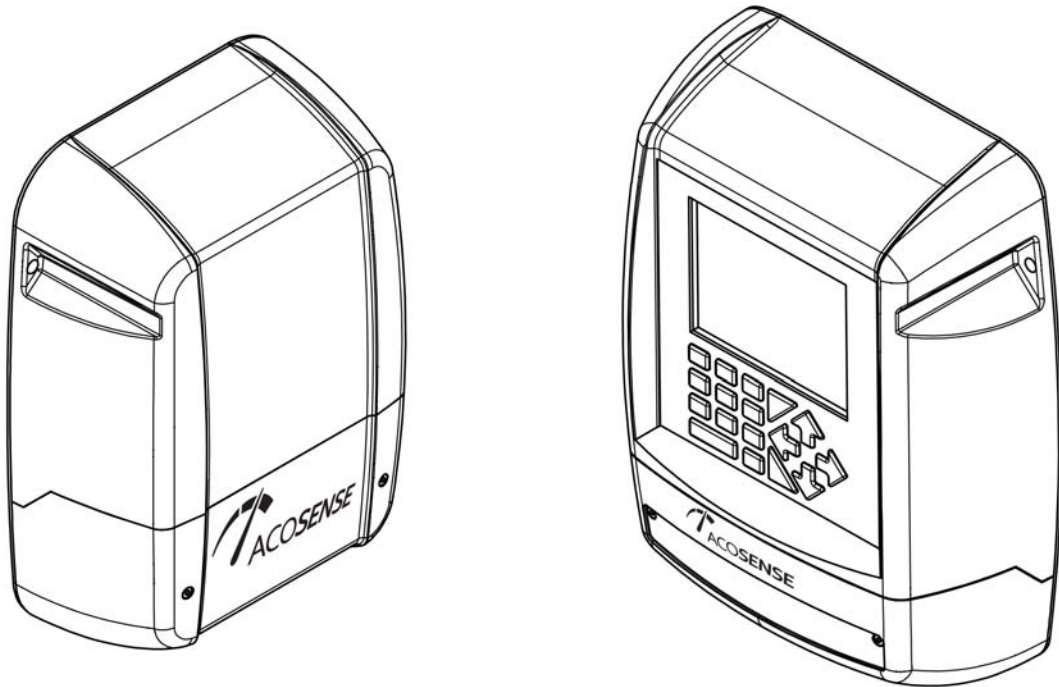


CHALMERS



Design and Development of Enclosures for the Acospector Acoustic Chemometer

– From idea to prototype

Master's thesis in Product Development

NIKLAS KALMTEG
CLAES SERNEVI

Department of Product and Production Development
Division of Product Development
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2011
Master's thesis 2011

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Department of Product and Production Development
Division of Product Development
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Cover:
Rendering of Acospector Acoustic Chemometer.

Chalmers Reproservice
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Abstract

This thesis covers the development process of an enclosure system for flow measuring equipment for industrial environments. It was performed on behalf of Acosense AB as a step in the commercialisation of their product, the Acospector Acoustic Chemometer. The product must be able to function in environments that put high demands on corrosion resistance, heat dissipation and ingress protection, and the purpose of the project was to encapsulate the electronics in a way that allows the instrument to be installed without exposing sensitive components. This installation should be possible for a technician to perform equipped with standard tools.

The project was divided into two major phases, the first of which was the adaptation of an off-the-shelf enclosure as a pre-series for evaluating the technology and use as a basis for further design work. The second phase aimed at developing a customised enclosure that was improved on a number of points in comparison to the standard solution in phase one. The design work was performed in accordance with established tools and methods described herein, covering steps from requirement specification to prototype production.

The project resulted in a pre-series enclosure system for evaluation of the company’s technology and initial sales, as well as a prototype of a promising customised system with suggestions for further work for enabling the product to enter new markets. To achieve a result viable for commercialisation, the project was performed in close collaboration with suppliers of the internal electronics, as well as with a design consultancy firm specialising in the area of interest.

Keywords: Acosense, active acoustic spectroscopy, enclosure, flow measuring, pulp, paper, product development

Preface

This work was carried out from December 2010 until May 2011 at the Department of Product and Production Development, Division of Product Development Chalmers University of Technology, Sweden. The authors are two students, with a Bachelor's degree in Mechanical engineering, attending the Master's programme of Product Development. The field of knowledge distributed throughout the education consists of amongst other basics in mechanical engineering, the value of user and customer pre-requisites and methods used for an efficient and effective development process. A similar knowledge is recommended for a satisfying understanding of the treated topic.

The entire project is supported and executed in close collaboration with the main stakeholder and proprietary of the product and related information, Acosense AB.

Acknowledgements

We would like to express our gratitudes and appreciation to the people at Acosense for relying on us with a large amount of responsibility and freedom of action, the people at Jelmtech AB for their support in the second phase of the project and to consulted industrial designer for contribution to the design. We are also grateful for the valuable input from people involved in the project such as instrument technicians and product champions. Finally, we would like to thank the people at the department of Design & Human Factors, the department of Product and Production Development and our supervisor for their support.

Göteborg May 2011

Niklas Kalmteg, Claes Sernevi

Acronyms

ATEX	Appareils destinés à être utilisés en ATmosphères EXplosibles.
CAD	Computer Aided Design.
CE	Conformité Européenne.
CSE	Chalmers School of Entrepreneurship.
DFA	Design For Assembly.
DFE	Design For Ergonomics.
DFM	Design For Manufacturing.
DFMA	Design For Manufacturing and Assembly.
DFX	Design For X.
EMC	Electromagnetic Compatibility.
EMI	Electromagnetic Interference.
HMI	Human-Machine-Interface.
IP	Ingress Protection.
ITF	Instrumenttekniska Föreningen.
JIT	Just-In-Time.
LPD	Lean Product Development.
NPD	New Product Development.
PCB	Printed Circuit Board.
SBCE	Set-Based Concurrent Engineering.
SLS	Selective Laser Sintering.
SPCI	Svenska Pappers- och Cellulosaingenjörersföreningen.
UL	Underwriter's Laboratories.

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1 Introduction

This report describes a master's thesis performed at the department of Product and Production Development at Chalmers University of Technology in the spring of 2011. The thesis was part of the company Acosense AB's finishing efforts of commercialising and launching a flow measuring device built on cutting edge technology.

1.1 Background

Acosense AB develops and produces an instrument for measuring a variety of parameters in process flows called Acospector Acoustic Chemometer (Acosense 2011, [1]). The invention originates from a number of patents from ABB who handed the invention to Chalmers School of Entrepreneurship (CSE) in 2007 for commercialisation. The project at CSE laid the foundation for what in 2009 became Acosense AB.

The underlying technology is called Active Acoustic Spectroscopy, meaning that an acoustic signal is emitted through the fluid and then received by sensors or accelerometers. By using multi-variate signal analysis properties such as viscosity, dry matter content etc. can be measured. Since it is a non-invasive procedure the product enables the measurement of properties in fluids, e.g. colloidal silica or black liquor, which up until now was difficult or even impossible to analyse without laboratory tests due to mechanical abrasion, corrosion and opacity.

Measuring is performed continuously and this real-time analysis gives the advantage of a more accurate process control. In the pulp and paper industry, which is a primary target group, the increased accuracy means that the efficiency of their recovery boilers can be improved by from one up to five percent. In terms of energy, an increased efficiency of 2.5 % would equate to half of Sweden's energy produced through wind power.

1.2 Purpose

In today's processing industry environments, many parameters must still be analysed and observed using laboratory samples [1]. Due to mentioned fluid properties obtaining a continuous observation of the flow is not possible using invasive measuring methods. However, a real-time process control is desirable to avoid unnecessary and costly stops in production. With the technology at hand, all of the above is within reach, but still the severe conditions at many of the measuring sites put high demand on the equipments durability. To protect the sensitive internal electronic components from damage or in worst case failure, a robust protective construction needs to be developed in order to guarantee operation of the product during its expected life time.

1.3 Objective

The main objectives and aim of this project is in a primary phase to develop a robust, intuitive and ergonomically designed demonstrator system. This system should consist of a control unit with appurtenant instrument unit for distribution amongst research partners and early adopters. This pilot version is intended to be assembled in-house using standard enclosure components and a custom designed panel with a keypad and a display. Using the first version as a high-end evaluative tool, further objectives are to develop a for its applications optimised enclosure protecting the components of the sensitive equipment from the outer elements as well as complying with stated and tacit customer needs and requirements. In order to structure the development process to reach efficiency and a satisfactory final result, the following research questions are posed:

- **How can the process be front-loaded to deliver a demonstrator in a short amount of time for future evaluative use?** In order to assess the market and start spreading the word, it is desirable to obtain a fully functioning demonstrator eliciting brand identity. It is also obliged to fulfill the functionality and requirements of the final product, an objective which must be met by rationalisation and a streamlined development process.
- **How can the hardware part of a Human-Machine-Interface (HMI) be designed to allow for an intuitive, comfortable and fool-proof use?** When using an HMI the user should get a sense of recognition. It is also important to evaluate the ergonomic aspects when it comes to operability, ability to view display etc. Is it then possible to produce an ergonomically correct product without compromising the high demands on environmental protection?
- **How can sensitive electronic components most efficiently be shielded from contaminating particles and fluids while still allowing interaction with the instrumentation?** With the demonstrator as a mediating tool, how can one develop a cost-efficient and aesthetically appealing industrial applicable solution to seal off sensitive electronic equipment from contaminants such as dust or fluids? The final solution should be optimised for its anticipated usage and be equal to or exceed the functional performance of its preceding demonstrator.

1.4 Scope

Within the frame of this project, research of existing literature on relevant topics as well as internal and external research of what is expected from the product-to-be is performed. In addition to the investigative literature search, further inspiration will be sprung from participation in a fair and through field studies on-site of current plants and refineries. This will result in a fully functioning demonstrator system from the initiating phase followed by another phase of development which will result in preparatory documentation for manufacturing of a customised protective structure for the already existing set of instrumentation. Here, a detailed design will be carried out resulting in a Selective Laser Sintering (SLS)-model and the final concept will be assessed from functionality and visual appearance. As the outcome of the project is a product intended for production and commercialisation, value was added by the support of an industrial designer and an external technology consultancy firm with years of experience in plastic design work. The pre-series product and prototype of the final concept will be part of the Acosense showcase at Svenska Pappers- och Cellulosaingenjörsföreningen (SPCI) in may 2011.

1.5 Limitations and Delimitations

In the first phase of the project, the enclosure development is limited to the selection and combination of standard parts from different sub-contractors with the exception of the operator panel and mounting solution for display and Printed Circuit Boards (PCB's), which are designed from scratch. This is in order to reach the desired level of functionality and customisation while dealing with a very tight schedule for the initial product launch. This limits the initial research to existing solutions within the field that can be utilised, leaving the aspect of visual appearance for the second phase. A clear interest in the product is already established, hence a complete market research is not considered necessary. Instead knowledge, material gathered by the company and product expertise is used.

This project does not handle any of the electronic components of the product, apart from the space for the PCB's and the different connectors. The physical arrangement of the cards is not covered either, as they are produced by two different companies who are responsible for their own parts. However, since these parts are closely related to those covered herein, the project is executed in a close collaborative manner with an open-ended communication with external project contributors and stakeholders. The cost estimation carried out in phase two is limited to the manufacturing of the molds used in the process since the cost for additional components is small in comparison with the one for the tool.

Production ramp-up and long-term testing of the durability and performance of the enclosures are not covered in this report, as the thesis work is too short for such testing to be performed after the completion of the product. This is mainly an issue in the second phase where an entirely new enclosure is developed, as the first phase uses existing components and structures with well documented reliability.

1.6 Environmental Aspects

The environmental impact of a successful implementation of the Acosense Acospector in Sweden's recovery boilers would be substantial considering the amounts of green energy that could be produced [1]. This project is a direct step in the commercialisation of the technology by making it possible to perform the measurements and calculations on site. Being a rather small product with low material use and little transportation but with harsh requirements on performance, the environmental impact is not possible to consider as the main issue in the development process. Gains that could be made by selecting an environmentally optimal material or manufacturing process seem pale in comparison with the effect of the overall system. The product also has an impact on the working environment of the workers in the process plants, as it reduces the amount of physical sampling they must perform, thereby reducing their exposure to the hazardous chemicals that are involved. The positive effect on the working environment is further enhanced by the consideration of ergonomics in the development process to make the product as user friendly as possible.

2 Theory

The following section describes the theories used for answering the questions posed prior to this project. It describes the theoretical part of the development process which is based on literature research as well as acquired knowledge in areas such as New Product Development (NPD), Lean Product Development (LPD) etc. Further, this section also describes the verification of a final design by design guidelines included in what is called Design For X (DFX) where the X represents a number of topics e.g. assembly, manufacturing and ergonomics. Also, in order to assure functionality and fulfillment of the strict safety requirements which must be applied to applications used in demanding environments like paper mills, a number of standards and classifications has been investigated.

2.1 Product Development Process

Markets of today are intense and global, fast growing and with rapidly changing technologies and therefore require an increased capability of foreseeing and meeting customers changing requirements (Wheelwright and Clark 1992, [2]). This poses a challenge, but might also function as a driver and facilitator for companies like Acosense since they are offering a new technical solution for those who want to be first with the latest.

A development process should hold a number of characteristics in order to increase the likeliness of a successful project; speed, efficiency and quality. Wheelwright and Clark describes this with three capabilities which should be striven for. Due to the intensified competition a capability of being fast and responsive is required. This implies shorter development cycles, but when acquired results in better targeted products. One also needs to possess the capability of high development productivity. The driving force behind this is a dramatic change found in product variety caused by more engaged and insightful customers. A final capability to satisfy the customer demands and take on the intense competition is to strive for distinct products. This capability calls for a creative approach with total product quality in mind. One step towards this capability can be through customer integration by including all possible aspects in a truly cross-functional development process.

2.1.1 New Product Development

There are different opinions on how to organise a development process. In this master's thesis, a structured method based on work by Ulrich and Eppinger was used. Their approach to product development predicates what is called NPD. This method was chosen due to its adaptability, and the fact that it has been communicated and spoken for during the master's programme which this thesis is performed within. A structured development process has a number of advantages: it reduces the otherwise inherited risk of moving forward without support for decision, the structure serves as a checklist to assure that no critical steps or issues are disregarded and the methods are to a large extent self-documenting (Ulrich and Eppinger 2008, [3]). The self-documentation can be used in so called lessons-learned purpose as feedback for future projects or for the education of company newcomers.

As an illustration of the sequence of steps included in a development process one depicts a generic model as the one seen in figure 2.1. The generic model is divided into a set of six phases.

Planning. The first phase constitutes of planning activities and is often referred to as phase zero since it precedes the actual project launch. This is to a large extent a phase

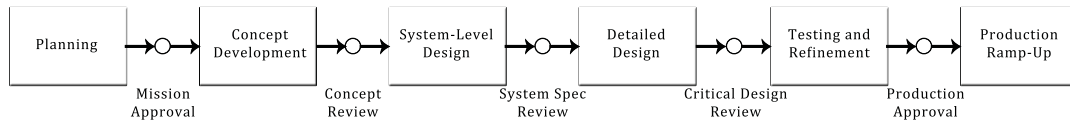


Figure 2.1: Model of a generic product development process (Ulrich and Eppinger)

of assessment with review of technology development and market constraints and opportunities. Resulting from this phase are project objectives with specifications of targeted market and limitations [3]. A detailed plan is composed to elicit major events and milestones for the duration of the project. However, this plan will also be complemented with information as more knowledge is gained on required tasks.

Concept development. At this next stage needs and requirements are identified and gathered in a specification. More precisely, Ulrich and Eppinger recommends following a five-step concept generation method which helps maintain a systematic approach. Step two and three are run in parallel. Concept generation can be stimulated with mediating tools such as mood boards and communicated through generic sketches of considered solutions. Generated concepts are screened out depending on set requirements. Screening is recommended to be performed systematically using elimination matrices such as Pugh-, Weighted Pugh- and Kesselring matrices.

1. Clarify problem. When generating concepts it is important to first identify and obtain understanding of the problem. After identification the problem is decomposed and focus is kept on critical subproblems.
2. Search for external solutions. An external search provides the development team with information on known solutions to the current or similar problems. This type of search involves interviews with lead users, expert consultation, searching patent databases, researching literature on the topic and benchmarking of related products. The outcome of this search can be existing conceptual solutions.
3. Search for internal solutions. Searching internally means taking advantage of in-house knowledge which in preceding phases has been found through e.g. user opinions and experienced pros or cons with previous work. This also involves common sense and engineering knowledge of all types which can facilitate idea generation. An internal search can lead to new concepts.
4. Explore systematically. In this fourth step in the concept generation the sub solutions found through this process is combined into complete solutions. The system exploration is a matter of organising solutions into feasible and interesting concepts. Organisation can be done using classification trees which illustrate relations between sub solutions which then becomes a potential solution. Another way of discovering concepts for further evaluation is using combination tables or morphological matrices.
5. Evaluate and assess found concepts using constructive feedback. An open minded evaluation is performed, although evaluation should to some extent be performed throughout the entire concept process and the project. One reflects on the carried out process to identify any possible missed parts of the design space. It is also recommended to consider if any obvious improvements easily can be implemented prior the forthcoming parts of the project.

The specification works as supporting documentation during design and as a basis for assessment of the final product. A span of conceptual products are derived and then evaluated based on their conceivable compliance with the stated requirements. A continuous revision of the requirements specification is made during the project to assure that no critical aspects are left out. A complete concept describes form, function and product features [3]. One can choose to continue the development of one or several of the promising concepts (this is also covered in section 2.1.2). An illustration of a typical concept selection process can be found in figure 2.2.

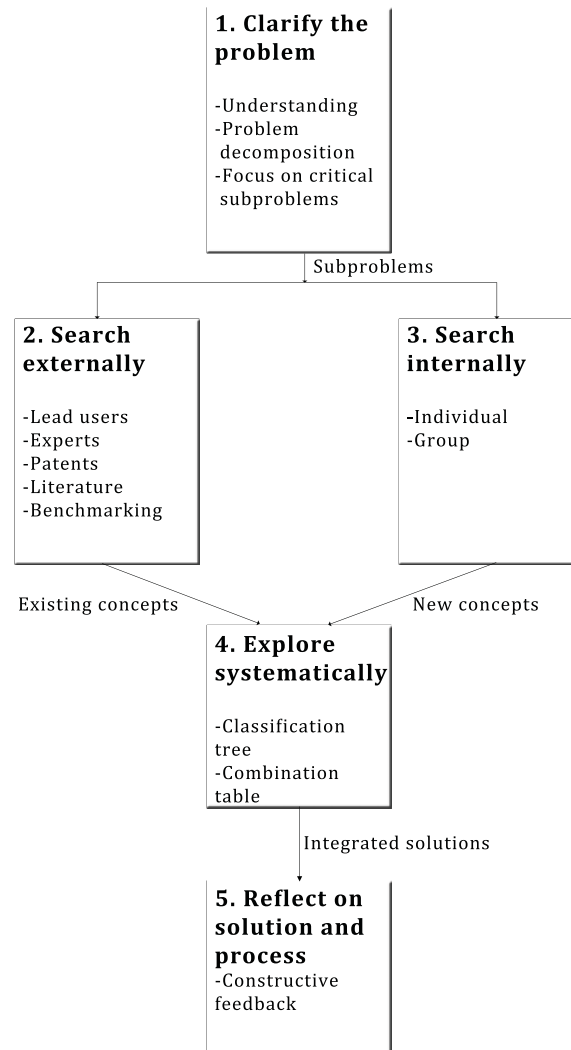


Figure 2.2: Generic concept selection process (Ulrich and Eppinger)

System-level design. In this phase one sets the architecture of the product and divides the observed system into a number of sub-systems and components. The outcome from this stage is usually a geometric representation of the product with a preliminary assembly flow description. Each of the subsystems is also described with a functional specification.[3]

Detailed design. The fourth phase includes the in-depth design of the final product. A detailed design does on one hand mean that the final geometric appearance of the product is defined. Further, materials and tolerances of the final product is determined and a compilation of standard components which can be acquired through an external supplier is prepared. Deliveries out of this fourth stage are geometric specifications in the form of drawings, specification of manufacturing method and a process plan of the product assembly. After setting the final design one can also perform a fair estimation of production cost.[3]

Testing and refinement. When reaching the phase of testing and refinement one usually constructs a number of pre-production products for evaluative use, prototypes. Prototypes exist in two maturity levels, early (alpha) and late (beta). The difference between the two are that alpha prototypes are often built with components intended for the final product but not necessarily delivered through the thought production channels. E.g. this could mean building an alpha prototype in 3D printing instead of injection molding which is more applicable for more extensive series production hence not for an evaluative product. Beta prototypes are instead built with intended components but might be assembled in an alternative manner.[3]

Production ramp-up. The final phase in the generic product development process model is also the last step before commercialisation of the finished product. The ramp-up involves training of production staff using the proper production system. Products manufactured during this period are not seldom used on-site of preferred customers for even more extensive testing in order to eliminate any possible remaining flaws or deficiencies.[3]

As the name implies a generic process model is a simplified version only to be seen as a guidance for structuring ones product development. In reality, the model is likely to require modifications in order to comply with occurring conditions. In most cases the process will call for a number of iterations to find a supreme final solution.

2.1.2 Lean Product Development

Lean has become a buzzword of our time. Originating in manufacturing systems with a major inspiration from the Toyota Production System Lean Production has been and is a method striven for by manufacturers worldwide (Womack et al. 2007, [4]). Characterising the lean approach are amongst other concepts like Just-In-Time (JIT) and Set-Based Concurrent Engineering (SBCE) with the objective of attaining a more responsive organisation for an organisation that delivers what the customer wants when they want it with value-adding activities in mind (Ward 2007, [5]).

In order to be successful it is important for an organisation to find a feasible relation between the technical and social part of the system. Treating these as interdependent factors in a work system is essential for a satisfactory working organisation (Clegg 2000, [6]). The technical part of such a system involves not only machines but also policies and standardised operational procedures of the organisation. The social part of the system is anything involving selection, evolution of and interaction between people and therefrom conceived culture within the organisation. This is the principal idea of socio-technical systems theory in which LPD has its origin where the socio-technical system can be seen to consist of three subsystems which are included in figure 2.3 (Morgan and Liker 2006, [7]).



Figure 2.3: Socio-technical system of LPD (Morgan and Liker)

Using these three subsystems, one can according to Morgan and Liker, extract the essence of LPD in terms of 13 principles. Below follows a selection of these principles which can be applied to and add value to this particular work. A process can be described as a flow, either of all kinds of information, material or the product making its way in the stream from conceptual idea to finished product.[7] First follows principles included in the process part of the system.

Define customer value to differentiate added value from waste. Adding customer value and hence eliminating waste is the focal point of LPD and therefore it is necessary to find what a potential customer values. There are two distinct types of waste: waste created by lack of engineering knowledge which might result in a poorly performing product and waste inflicted by the current development process. The risk of falling for the first category of waste is decreased by acquiring a solid foundation of knowledge of the particular product.[7]

Maintain a maximum of design space while front-loading the development process. By commitment of resources in the projects initial phase, i.e. front-loading, a vast amount of possible solutions can be identified and the important factor of cross-disciplinary approach can be implemented early. This way of deriving several concepts for further evaluative purpose is what is called SBCE and this contributes to a greater possibility of finding an optimal solution.[7]

Level the process of Product Development. By improving the development process after facing the challenges within, LPD requires a process free of waste to minimise the time to market. This can be done based on experience gained from preceding projects or through rationalising or streamlining the development process at hands.[7]

Create a robust development environment to minimise variation and allow for flexibility by an extensive use of standardisation. Standardisation applies to all parts of the development process from design to engineering competence. The challenge is to standardise while maintaining a certain level of creativity.[7]

In the 'people subsystem' one finds another set of principles which, depending on the magnitude of the project, has different level of applicability or relevance.

Set up an organisation balancing functional expertise with a cross-functional approach. To achieve a streamlined and efficient development organisation, coordination between involved functions is a critical matter. By maintaining a continuous communication up- and downstream, subsystem interdependencies can be identified and used to its fullest. This must, however, be done while still considering the preservation of functional expertise for an end result in its prime.[7]

Integrate and engage the suppliers into the Product Development System. Suppliers should be managed and cared for in the same manner as you would for internal manufacturing and production. It is not rare for the suppliers to possess valuable experience that should not be overlooked. Hence, it is recommended to enroll suppliers at an early stage of the project.[7]

The third and last subsystem, technology, is not made up solely of hard tools and the literate perception of technology. Rather, all aspects supporting development must be considered.

Obtain comprehension for issues and solutions by using simple visual communications. By using visual aids for communication, it is easier to reach understanding between functions and people. Visualisation can be used to mediate a feeling through e.g. mood boards, but is also valuable when communicating proposals, problem solutions, status reports and benchmarking analysis.[7]

Identify tools for standardisation and organisational learning. This principle treats the idea of lessons learned, i.e. how to gather and transfer gained knowledge to forthcoming projects. This ranges from improvements that can be introduced in the development process down to detailed component design which can be altered for a more satisfactory performance.[7]

Implementation of LPD is an evolutionary process that takes time but, separate elements and inspiration can be introduced for a better product development process.

2.1.3 Agile Development

Flexibility has become an increasingly desired quality in Product Development Systems due to shorter time to market, shorter product life cycles and reoccurring changes in specifications known as the moving target. The increase in product complexity also leads to an increased difficulty of forecasting requirements.(Thomke and Reinertsen 1998, [8])

Environments which would benefit from agile development among others are those with a high level of uncertainty and projects that require some unique competence or are signified by an urgent finalisation (Chin 2003, [9]). These three characteristics combined are what causes changes in project requirements and requires a change in focus from extensive planning to execution.

There are two kinds of uncertainties in projects: internal and external (figure 2.4). The internal uncertainty is such that it most often to some degree can be controlled by managing scope, time line and finances. The external uncertainty on the other hand are those factors that do not fit within the project. This can be a competitors move, or for example uncertainties adopted from the surrounding business environment; suppliers, customers etc. Uncertainties can mean radical changes to the project, but does not have to mean that changes need to be made to the original objectives or time line. Rather

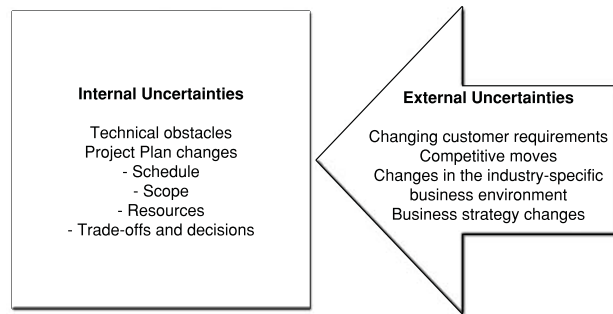


Figure 2.4: Internal and External Uncertainties in Project Management (Chin)

then it requires one becoming agile and responsive and continuously adopt to requirement changes.

When implementing the required prerequisites to obtain an agile organisation the value of having a cross-functional team is emphasised. The dynamic which results from this type of arrangement is irreplaceable when it comes to identifying issues and perform rapid changes in the chosen project path.[9]

2.2 Electronic Packaging Design Considerations

In the development and design of packaging for electronic devices, one must consider a vast field of technologies and concepts. This calls for an large amount of knowledge, a cross-functional team or a development environment which allows for assimilation of know-how. Aspects to consider could e.g. be management of internal and external thermal loads, handling of product environment and Electromagnetic Compatibility (EMC) etc.(Blackwell 2000, [10]) The following section describes topics in direct relation to or with interdependence to areas of this thesis intended design space.

2.2.1 Electromagnetic Compatibility

With the increase in communication, computation and automation, the number of electronic circuits is constantly rising. Increased number of electronics in combination with smaller circuits also means that they are packed into a tighter space. This is the background to the growing issue of Electromagnetic Interference (EMI), which is the effect that circuits exert on each other.(Ott 2009, [11])

When designing electronic equipments one must consider the interference which circuits generate or pick up from surrounding electronics. These considerations are regulated by standards in what is called EMC.

“EMC is the ability of an electronic system to (1) function properly in its intended electromagnetic environment and (2) not be a source of pollution to that electromagnetic environment.”[11]

EMC has two aspects: emission and susceptibility. Susceptibility can be described as how the product is affected by interferences and noise from the surrounding environment. The opposite of susceptibility is immunity, the level of immunity is the environment in which the device is functioning with satisfactory performance with a certain margin of safety. Emission is the disturbance which a product causes to its surrounding devices and circuits. By controlling the emission one controls the environment and minimises the level of EMI.[11]

Engineering for EMC can be approached in two different manners, crisis approach and systems approach. The idea of crisis approach is to disregard EMC as a design constraint and complete the development up until a functional design. Once the development process is finished the product is put to its test in the planned environment where it is studied to find if its level of EMC is satisfactory. Any potential changes are made ad-hoc and are if required guaranteed to inflict an increased cost. The increased cost can be explained by the fact that available techniques for lowering device susceptibility decreases as development progresses. This means that a change could require separate add-ons rather than being implemented in the intended design. The systems approach means that EMC is introduced early in the development process where it is included in the requirement specification. Considering the problems of interference early in the process is therefore often the best alternative as well as least expensive.[11]

According to the EMC directive measuring instruments such as the one treated herein is excluded from the susceptibility criteria, but the level of emission must be evaluated and considered.(Guide for the EMC Directive 2004/108/EC, [12])

2.2.2 Thermal Management

When designing an electronic enclosure one must consider the thermal conditions both internal and external. The temperatures must not exceed critical levels which affects material properties or jeopardises performance of sensitive electronic components. In case of non-operable temperatures, one must address these issues and find a solution which lowers them. This could be passive elements such as cooling flanges or heat sinks, or active elements, e.g. fans or liquid cooling.[10]

Interior temperatures of interest are the junction temperature, T_j , which is the temperature inside the circuits of the components and the enclosures ambient temperature, T_a . Maximum junction temperature is normally specified in a product data sheet from the circuitry supplier. These two temperatures are interrelated, as higher ambient temperature yields a higher junction temperature. The ambient temperature depends on the generated heat and dissipation rate, which can be anticipated due to temperature in the surrounding environment.[10]

In order to evaluate reigning conditions, fundamental knowledge of heat transfer can be applied. There are three ways in which heat is transferred; convection, conduction and radiation (Incropera and Lavine 2006, [13]). In many cases the effect of radiation is neglected, due to an observed control volume small in relation to the surroundings, to facilitate the calculations. A convenient approach can then be to use the overall heat transfer coefficient, denoted by U , that is used to determine the heat transfer rate. The heat transfer rate is defined as

$$q_x \equiv UA\Delta T \quad (2.1)$$

where ΔT is the total difference in temperature from inside to outside of the enclosure and A is the area normal to the direction of heat transfer. U is related to the total thermal resistance and an analogy with a corresponding electric circuit can be found (figure 2.5).

The overall heat transfer coefficient is defined as

$$U = \frac{1}{R_{tot}A} = \frac{1}{\frac{1}{\alpha_1} + \frac{d}{\lambda} + \frac{1}{\alpha_2}} \quad (2.2)$$

where R_{tot} is the total thermal resistance, α the convection heat transfer coefficient with subscript 1 and 2 for internal and external medium respectively, d is the thickness of the wall and λ is the thermal conductivity of the wall material.[13]

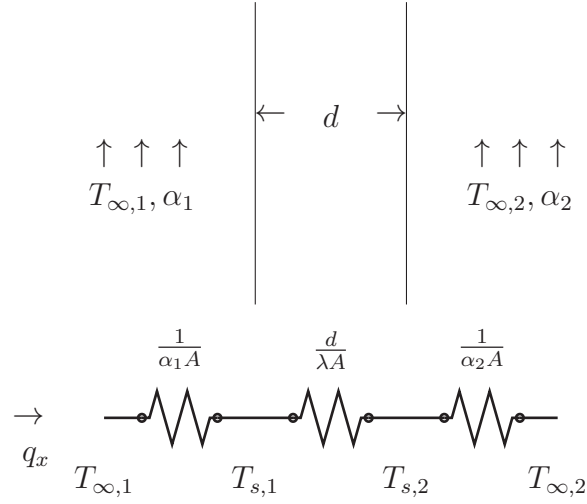


Figure 2.5: Analogy with corresponding electric circuit (Incropera and Lavine)

Using the so called *Lumped Capacitance Method*, one can balance the generated and stored internal energy with the rate of heat loss from surface to the surrounding environment. This yields the following expression for the previous stated requirement.

$$\dot{Q}_{in} - \dot{Q}_{out} = 0 \quad (2.3)$$

The balance between induced and dissipated energy contains several terms as stated below

$$\dot{Q}_{in} - \dot{Q}_{out} = UA_{wall}(t_o - t_r) + UA_{window}(t_o - t_r) + \dot{Q}_{ekv} = 0 \quad (2.4)$$

where U is the overall heat transfer coefficient from equation (2.2), A_{wall} the exterior surface area of the enclosure, $(t_o - t_r)$ the difference between internal and external temperature and \dot{Q}_{ekv} induced energy, i.e. heat generated by internal electronics.[13] A_{window} can be used in the case of non-uniform material usage. This could compare to the use of a metal plate as back piece in combination with a plastic enclosure to increase its capability of transferring heat away from the internal components.

These equations can be used for analysing the anticipated maximum temperature within the enclosure during certain environmental conditions. By doing so, one can find the equipments highest allowed temperature for operation. Equation (2.4) implies that the sought after internal temperature for a uniform enclosure can be approximated as

$$t_r = \frac{\dot{Q}_{ekv}}{UA_{wall}} + t_o \quad (2.5)$$

The calculations yields an approximative value for steady-state conditions, i.e. dynamic properties are left out.[13]

Based on the derived value for the maximum temperature obtained the maximum temperature can then be determined within the circuitry of internal components, T_j . The following expression is used for this purpose

$$T_j = T_A + [(\theta_{jc} + \theta_{ja}) * P_D] \quad (2.6)$$

where ambient temperature, T_A , is the one that was expressed as the internal temperature of the enclosure i.e. $t_r = T_A$. Variables θ_{jc} and θ_{ja} are thermal resistances for junction-to-case and junction-to-air respectively. Resistance for heat transferred from junction to air can be manipulated using a heat sink or similar to lower the junction temperature. Hence, the purpose of these calculations is to find whether an additional cooling solution of the processing unit is required. P_D is the dissipated energy which should be diverted from the sensitive components.[10]

2.3 Design For X

DFX is an umbrella term for different design methodologies, where the X stands for different processes and properties such as Design For Manufacturing (DFM), Design For Assembly (DFA) and Design For Ergonomics (DFE). These provide tools and guidelines for the development process to reduce lead times and increase performance of the product.

2.3.1 Design For Ergonomics

In recent years, the focus on DFE has grown as companies have realised the benefits for everyone in the system. Individuals experience an increased safety and comfort, the companies have increased productivity and better products and society benefits from lower sick leaves and better economy.(Bohgard et al. 2009, [14]) The field is divided into two main research areas; physical and cognitive ergonomics. The physical aspect is probably what most people think about when they hear the word ergonomics, as it is usually referring to a design that is intended to minimise the stress put on the users body and thereby reducing the risk of work related injuries. This is an important part of the ergonomics field, since it is closely connected to some of the benefits described earlier in terms of increased safety for the individuals and lower sick leaves in society. What many people might overlook, however, is the study of cognitive ergonomics: how user friendly a product is and how well it facilitates interaction. This connects to the other benefits of ergonomics, as productivity increases and the products are regarded as better if the systems are easy to understand and to use.[14]

Introduction of physical ergonomics begins in the early design phases. It is important to know who the target customer is, as it affects the anthropometrics that are used to determine the measurements of the product.[14]

Designing a product for good cognitive ergonomics concerns bridging the Gulf of Evaluation and the Gulf of Execution (Norman 1988, [15]). The Gulf of Evaluation is, simply put, when the product sends the user a message about its status or similar, but the user has difficulties interpreting the information he/she receives. A good example of this would be a battery charger with only one light that is either red or green, as this makes it difficult for an inexperienced user to understand if the green light means that it is charging or that it has finished. The Gulf of Execution is, similarly, when the user has a clear intention with his/her interaction with the product, but does not understand how to achieve it. This could be something as simple as answering a phone call, as todays touch screen mobile phones does not always show clearly how this action should be performed. These factors are difficult to assess before a concept is created in the way that it is possible to design for physical ergonomics using the anthropometry of the intended user.

The transmission of inputs to a piece of equipment by hand or foot is done by controls (or activators as they are called in ISO standards). The results of the control inputs are shown either in displays and indicators or in the behavior of the machine. These control actions are distinguished into the following types of actions [10]:

- Activate or shut off equipment, e.g. change the TV channel
- Make a discrete setting, e.g. set the thermostat temperature
- Make a quantitative setting, e.g. adjusting the volume on the stereo
- Apply continuous control, e.g. steering an automobile
- Enter data, e.g. on a computer keyboard

The controls for these actions should be compatible with stereotypical common expectations in terms of type, size and motion. Operations that require fine control and small force should be performed with the hands, whereas gross adjustment and large forces are usually exerted with the feet. Target values and design guidelines can be found in literature and are based on extensive research on the field.[10]

2.3.2 Design For Manufacturing and Assembly

Design For Manufacturing and Assembly (DFMA) is used for three main activities (Boothroyd 2002, [16]):

1. To base concurrent engineering studies on and provide guidance to the design team by quantifying the improvements in simplification of the product to reduce manufacturing and assembly costs.
2. As a tool for benchmarking studies of competitors products and quantify difficulties in manufacturing and assembly.
3. As a should-cost tool to help negotiate suppliers contracts.

The work with DFM and DFA is founded on two basic principles; reduce the number of assembly operations by reducing the number of parts and make the assembly operations easier to perform. A General Motors executive once stated that:

“DFM/DFA is a primary driver of quality and cost improvement.”,

“It provides technical improvements to both product and process.”

and that

“DFM/DFA is not an option - it’s a requirement.”

Before the studies of DFMA started, there were recommendations published known as “producibility guidelines” in the 1960s. These guidelines stated, among other things, that it would be inherently less expensive to manufacture parts made from several simple-shaped components rather than making one part with a complex shape and that any assembly costs are more than offset by savings in part costs. It turned out, however, that they were wrong on both accounts, as not only did the part costs decline when DFMA was introduced and comparisons were made, but when studying the costs for assembly, storage, part handling etc. it became clear that huge savings could be made. In order to guide the designer in reducing the part count, the DFA methodology provides three criteria against which each part must be examined:

1. During the operation of the product, does the part move relative to all other parts? Only large motions are considered - motions small enough to be accommodated by elastic elements are not sufficient for a positive answer.

2. Must the part be of a different material than or be isolated from all other parts?
Only fundamental reasons concerned with material properties are acceptable.
3. Must the part be separate from all other parts to make necessary assembly or disassembly of other separate parts possible?

If the answer to any of these questions is Yes, the part must be separated, otherwise it can be integrated in an adjacent structure.[16]

Other dictated recommendations are to incorporate standard components, standardisation of the design and generous tolerancing to enable the benefits of mass production even in low quantity products.(Bralla 1998, [17])

Furthermore, there are several guidelines for the shape of the parts depending on their manufacturing and assembly process. Parts that are to be assembled manually, for instance, should be made symmetrical as far as possible to remove the step of having to turn the part around, or to be made pronouncedly asymmetrical to clearly show how it should be assembled. Parts mated by insertion should have chamfers and generous clearance to reduce resistance, but not enough so to cause jamming. The use of guidelines in the design process is a good start, but is not enough as they provide no means by which to evaluate the design quantitatively for its ease of assembly. There is also relative ranking of all the guidelines indicating which give the greatest improvement on handling, insertion and fastening etc. meaning that there is no way for the designer to know which guidelines to emphasise during the product design. Simply put, there is no estimate of how much easier it is to assemble one design with certain features than another with different features if a systematic DFMA evaluation method is not used.[16]

Design for Injection Molding Injection molding is a manufacturing process mainly used for polymers. It involves heating the material until it melts and then injecting it into a pre-manufactured form (see figure 2.6 (Bralla 1998, [17])) giving the product its final shape and characteristics upon cooling and solidification. Compared with more traditional materials, polymers generally allows for more complex parts and features such as incorporated snap fits allowing reduction in the number of parts. The vast range of polymers with different properties is beneficial when dealing with severe environmental conditions such as corrosion and mechanical wear, since one is likely to find a material applicable for the particular product.[16]

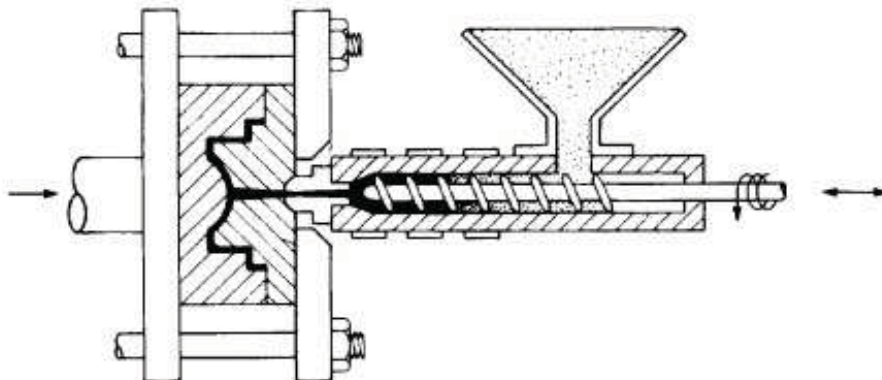


Figure 2.6: Injection molding tool (Bralla)

By the nature of the process, injection molding is mostly done using thermoplastics due to e.g. their good flow characteristics. Mechanical properties of thermoplastics can usually be improved using fiber reinforcements decreasing the polymers susceptibility for

mechanical wear. A number of polymers used for injection molding are shown in table 2.1[16] with typical values for different material properties.

Table 2.1: Polymers applicable for injection molding (Boothroyd)

Thermoplastic	Yield strength (MN/m ²)	Elastic modulus (MN/m ²)	Heat deflection temperature (°C)
High-density polyethylene	23	925	42
High-impact polystyrene	20	1900	77
Acrylonitrile-butadiene-styrene (ABS)	41	2100	99
Acetal	66	2800	115
Polyamide (6/6 nylon)	70	2800	93
Polycarbonate	64	2300	130
Polycarbonate (30% glass)	90	5500	143
Modified polyphenylene oxide (PPO)	58	2200	123
Modified PPO (30% glass)	58	3800	134
Polypropylene (40% talc)	32	3300	88
Polyester terephthalate (30% glass)	158	11,000	227

Designing for injection molding requires knowledge about the process and its procedure. Considerations to be made involves material selection, type of fasteners to be used, material thickness (stiffness in relation to producibility), tool part lines and many more. These parameters will affect the appearance of the final design.[16]

To avoid production defects such as sinks, flashes and skewness there are a number of methods to improve the feasibility and final result (see figure 2.7 (Custompart.net 2011, [18])). To avoid sinks, one strives for an uniform material thickness (figure 2.7b). Flashes could result from a lack of draft angle which is required to allow for ejecting the part from its mold (figure 2.7d). To facilitate ejection, one implements so called ejectors which are elements with a protruded surface onto which the tool can apply pressure. Skewness can arise on a slender part which tends to cool faster than the rest of the component and is counter measured using so called ribs which straightens the structure (figure 2.7f) rather than increasing the material thickness. Fasteners for assembly or mounting of e.g. PCB's are incorporated into elevated structural supports called bosses. In order for the bosses to be stable as well as not interfering with the intended quality, these can be supported by extending supports to adjacent walls (figure 2.7h).

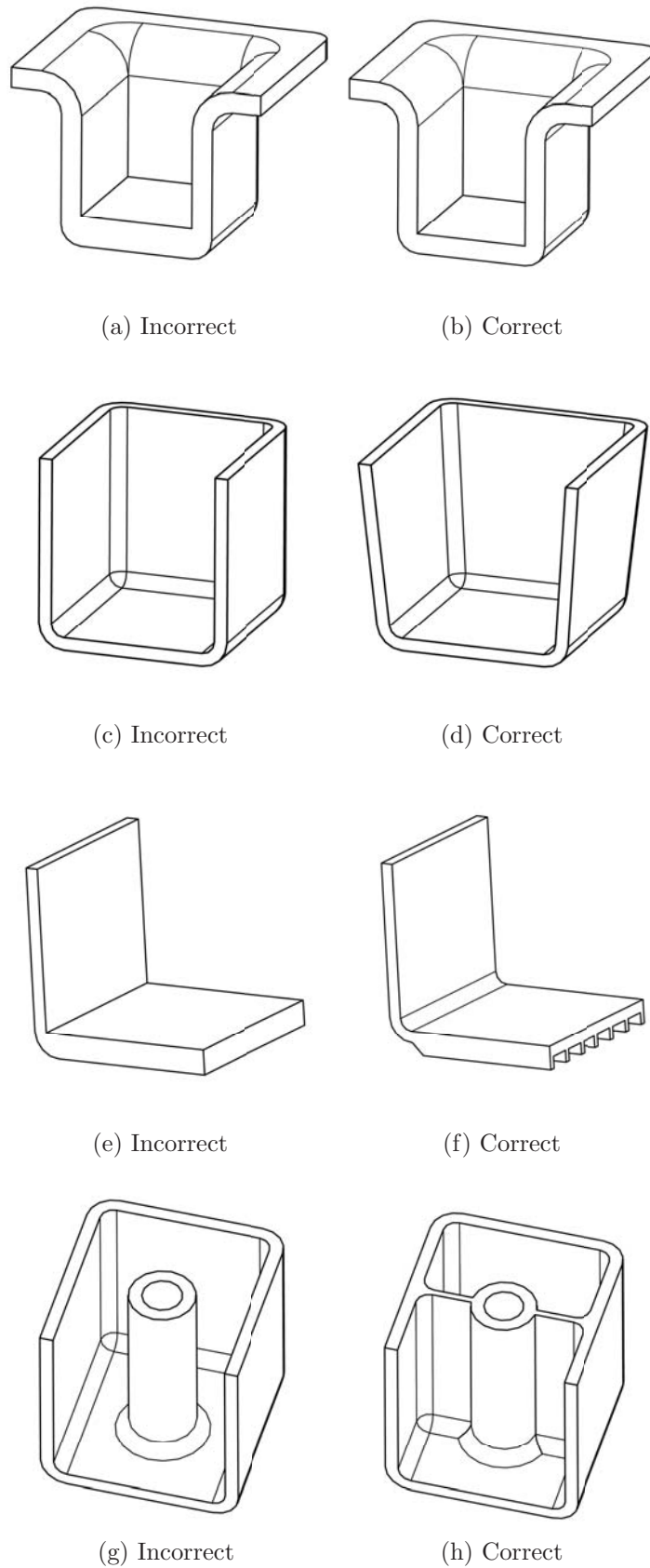


Figure 2.7: Possible defects and countermeasures (Custompart.net)

Joining with polymeric components can be done using welding, gluing, rivets, snap fits, screw fasteners or press fit.

Fastening and assembly with screws can be approached either directly in the component with self-tapping screws or one can use threaded metal inserts which are press fitted into the material. Screw fasteners has the advantage of being reversible and strong joints which allows for interaction between different materials.

Snap fits uses the flexibility inherited in the polymer for fast assembly without requiring any additional components.(Klason and Kubat, [19])

Manufacturing Cost Estimation Several factors affect the final cost of a product e.g. complexity, size, required number of tools, tolerances etc. However, to make a preliminary estimation of product tool cost it has been shown that the base cost is a function of surface area of the selected mold base plates and combined thickness of the cavity and core plates. This relation can be described by the following expression [16]

$$C_b = R_e(1000 + 0.45A_c h_p^{0.4}) \quad (2.7)$$

where C_b is the derived cost of the mold base in Swedish Kronor (SEK), R_e is the recent exchange rate for conversion from US dollars, A_c is the area of the mold base cavity part in cm^2 , h_p is the combined thickness of cavity and core plates in mold base given in cm. A mold base is selected based on part depth, the projected area and required number of cavities in the mold. One must also take into consideration space required for additional tool movements such as side pulls, which are used to produce geometrical undercuts. Hence, to minimise the cost, one wants to avoid increased geometrical complexity if possible.[16]

Apart from the mold base cost, one must according to work by Boothroyd also consider the cavity and core manufacturing costs. Additional work on the mold can relate to the ejection system, requirement of extra support pillars and integration of coolant systems. Knowledge of number of ejector pins is required for a fair estimation. This specific design detail is rarely known at an early stage but the number can be approximated from

$$N_e = A_p^{0.5} \quad (2.8)$$

where N_e is the required number of ejector pins and the A_p is the projected part area in cm^2 . This is further used to determine the approximate number of manufacturing hours used for the ejection system of a part from the following expression.

$$M_e = 2.5A_p^{0.5}h \quad (2.9)$$

As mentioned, an increased complexity adds to the product cost. A scoring of part complexity is therefore introduced in order to derive manufacturing hours associated with a parts geometrical features for one cavity and appurtenant core as

$$M_x = 5.83(X_i + X_o)^{1.27}h \quad (2.10)$$

where X_i and X_o is a number that ranges between zero and ten that denotes the inner and outer complexity respectively. For a preliminary analysis, a quick judgment of these numbers can be used for the proceedings of the cost estimation.

Apart from the parts complexity, the size of what is intended for molding also affects the cost. For a very simple geometry, the number of manufacturing hours for one complete tool, cavity and core, can be described by the expression

$$M_{po} = 5 + 0.085A_p^{1.2}h \quad (2.11)$$

Adding the number of hours obtained from each of the expressions in equation (2.9), (2.10) and (2.11) yields an estimate base for the numbers of manufacturing hours to produce one mold for a given size and level of complexity.

In order to complete the estimation six additional factors needs to be taken into concern:

1. Requirement of retractable side-pulls or internal lifters of the core.
2. Requirement for unscrewing cores to produce integrated screw threads.
3. Finish and visual appearance specified for the parts surface.
4. Applied average dimensional tolerances of the part.
5. Requirement for surface texture.
6. Shape and complexity of the surface across which the mold separates. This line is in design terms named the parting line.

Based on factors stated above, the cost estimation can be complemented to attain a more accurate result. The factor of appearance level is posed as a percentage increase to the preceding estimation of required manufacturing hours. These are presented in table 2.2.

Table 2.2: Increased cost due to various levels of appearance (Boothroyd)

Appearance	Percentage increase
Not critical	10
Opaque, standard	15
Transparent, internal flaws or flashes allowed	20
Opaque, high gloss	25
Transparent, high quality	30
Transparent, optical quality	40

From similar reasoning it follows that one must include the effect of defined tolerances. The specified tolerances must be within the capabilities of the manufacturing method. As always, finer tolerances inflicts an increase of cost leaving the tool manufacturer within a smaller range of tolerances to work with. As with the surface appearance, this means percentage increases to the cost of required tool components. These percentages are stated in table 2.3.

The last factor to be considered is the shape of the surface at which the parting line is located. A more complex shape of this surface yields an increase in manufacturing hours of the mold. This is described in

$$M_s = f_p A_p^{1/2} h \quad (2.12)$$

Table 2.3: Increased cost due to finer tolerances (Boothroyd)

Tolerance level	Tolerance description	Percentage increase
0	All greater than ± 0.5 mm	0
1	Most approximately ± 0.35 mm	2
2	Several approximately ± 0.25 mm	5
3	Most approximately ± 0.25 mm	10
4	Several approximately ± 0.05 mm	20
5	Most approximately ± 0.05 mm	30

Table 2.4: Part surface factor (Boothroyd)

Parting surface	Factor (f_p)
Flat parting surface	0
Inclined parting surface or one with a single step	1.25
Two to four simple steps or simple curved surface	2
More than four simple steps	2.5
Complex curved surface	3
Complex curved surface with steps	4

where A_p is the cavity's projected area, f_p is the factor of the parting plane described in table 2.4 and M_s is the additional hours of mold manufacturing required in case of non flat parting surface.

All of the aforementioned expressions and considerations form the basis for the final cost estimation which is performed using a scoring table (table 2.5) where all aspects are taken into consideration.

Finally, to attain the estimated cost of tool manufacturing, the accumulated score is multiplied with an average hourly rate for tool production.[16]

2.4 Protection Classes

In product development, a constant focus should be kept on end customer and its environment. When setting the final specifications for a product, it is important for the user to know that the product is fully functioning and can be safely operated during reigning conditions. Hence, a number of standards classifications and third-party certifications exist to assure fulfillment of this type of demand. Those related and considered in this project are presented in this following section. Treated protection classes makes a foundation for a future certification in accordance to Conformité Européenne (CE).

Table 2.5: Cost estimation scoring table (Boothroyd)

	Points
(i) Projected area, (A_p)	Eqs. (2.9) and (2.11)
(ii) Geometric complexity, X_i and X_o	Eq. (2.10)
(iii) Required number of side-pulls	65 for each
(iv) Required number of internal lifters	150 for each
(v) Required number of unscrewing devices	250 for each
(vi) Surface finish	Table 2.2 applied to (i) and (ii)
(vii) Level of tolerance	Table 2.3 applied to (ii)
(viii) Texture	If required, add 5% to (i) and (ii)
(ix) Parting plane	Table 2.4, use f_p in eq. (2.12)

2.4.1 ATEX

A product or equipment used in explosive atmospheres must be classified according to the Appareils destinés à être utilisés en ATmosphères EXplosibles (ATEX) directives as of 2006 to protect employees from explosion risk. The two ATEX directives are ATEX 137, the workplace directive, and ATEX 95, the equipment directive, (Directive 94/9/EC, [20]) which is further introduced in the following chapter.

Following definitions apply when describing the environment in which the ATEX classification is relevant.[20]

Explosive atmospheres: Mixture with air, under atmospheric conditions, of flammable substances in the form of gases, vapors, mists or dusts in which, after ignition has occurred, combustions spreads to the entire unburned mixture.

Potentially explosive atmosphere: An atmosphere which could become explosive due to local and operational conditions.[20]

Atmospheric conditions: A temperature range of -20°C to 60°C and a range of pressure between 0.8 bar and 1.1 bar may be appropriate as a basis for design and intended use of products.(ATEX guidelines 2009, [21])

The hazardous areas are classified into zones based on the frequency and duration of the occurrence of an explosive atmosphere.(ATEX 2009, [22]) These are described in table 2.6.

The ATEX directory also categorises equipment into two groups [21]:

- Group 1 equipment is intended for use in mining applications and is divided into M1 and M2, where M1 is equipment that must continue to operate when a potentially explosive atmosphere is present and M2 identifies equipment that does not.
- Group 2 is intended for all other applications and is divided into categories 1, 2 and 3. Category 1 equipment is intended for use in Zone 0, Category 2 in Zone 1 and Category 3 in Zone 2. Category 1 equipment can, however, also be used in Zones 1 and 2 as well, etc.

Table 2.6: ATEX Zones (Directive 94/9/EC)

Zone	Description
0	A place in which an explosive atmosphere consisting of a mixture with air of dangerous substances in the form of gas, vapor or mist is present continuously or for long periods or frequently.
1	A place in which an explosive atmosphere consisting of a mixture with air of dangerous substances in the form of gas, vapor or mist is likely to occur in normal operation occasionally ($t < 1000\text{h/year}$).
2	A place in which an explosive atmosphere consisting of a mixture with air of dangerous substances in the form of gas, vapor or mist is not likely to occur in normal operation but, if it does occur, will persist for a short period only ($t < 10\text{h/year}$).
20	A place in which an explosive atmosphere in the form of a cloud of combustible dust in air is present continuously, or for long periods or frequently.
21	A place in which an explosive atmosphere in the form of a cloud of combustible dust in air is likely to occur in normal operation occasionally.
22	A place in which an explosive atmosphere in the form of a cloud of combustible dust in air is not likely to occur in normal operation but, if it does occur, will persist for a short period only.

There are some common requirements for equipment according to the ATEX directive, including, but not limited to, that the manufacturer should prevent the formation of explosive atmospheres by the equipment itself and that the ignition of explosive atmospheres should be prevented taking into account the nature of every electrical and non-electrical source of ignition. The product must also be constructed of materials that must not trigger explosions, taking into account foreseeable operational stresses and reactions between the materials used and the constituents of the potentially explosive atmosphere. If parts which can ignite an explosive atmosphere are placed in an enclosure, measures must be taken to ensure that the enclosure can withstand the pressure developed during an internal explosion and prevents the transmission of the explosion to the atmosphere surrounding it. A product conforming to these requirements is marked by the ATEX logotype (see figure 2.8).



Figure 2.8: ATEX Logotype (ATEX Guidelines)

2.4.2 UL

The Standard for Tests for Flammability of Plastic Materials for Parts in Devices and Appliances Underwriter's Laboratories (UL) 94 are small scale tests. These evaluate the flammability of polymeric materials in response to small, open flames or radiant heat sources under controlled laboratory conditions. This means that the results of most UL 94 flammability tests are not applicable to materials with a thickness greater than 13 mm or parts with a surface area exceeding 1 m². (The misunderstood fire test 2007, [23])

UL 94 is tested in three different ways; Surface Burn for UL 94 5VA and 5VB, Vertical Burn for UL 94 V-0, V-1 and V-2, and Horizontal Burn for H-B rating (table 2.7). (UL 94 general information 2007, [24])

The horizontal test is generally considered the easiest test, which is why UL 94 H-B is considered to be the lowest rating, and is made by letting a ½" x 5" specimen held horizontally be applied to the free end for 30 seconds or until the flame front reaches 1". If combustion continues, the duration is timed between the 1" and 5" mark. A 3 mm thick sample will be classified UL 94 H-B if it has a burning rate of less than 3" per minute or it stops burning before the 5" marking. A set of 3 specimens are tested, and if one fails to comply, a second set is tested of which all must comply. UL 94 H-B rated materials are generally acceptable for portable, attended appliance enclosures, such as hair dryers. [24]

UL 94 Vertical burning tests are performed by holding a ½" x 5" specimen at one end in a vertical position and applying a burner flame to the free end of the specimen for two 10 second intervals separated by the time it takes for the flaming combustion to cease after the first application. Two sets of 5 samples are tested, with the following data recorded for each: Duration of flaming combustion after first and second burner application, Duration of glowing combustion after second burner application, Whether or not flaming drips ignite a piece of cotton placed below the tested sample and Whether or not the specimen burns up to the holding clamp. The UL 94 V classifications are typically acceptable for portable, unattended appliances, e.g. coffee makers. [24]

The UL 94 Surface Burn test is performed by applying a flame larger than the one used in the Vertical Burn Testing to a test bar for five times for 5 seconds. The recorded data is the duration of flaming combustion after the last application and whether or not there is a burn-through. UL 94 VA is the most flame retardant rating. [24]

2.4.3 Ingress Protection

In order to minimise risks of electric shocks, fire and explosion, high demands are put on protection of electronic equipment in harsh environments (IP-klassning 2011, [25]). This can be an environment with a potential risk of penetrating pollutants such as dust, corrosives and fluids. Requirements are regulated in product standards for electrical safety and potentially explosive environments.

The Ingress Protection (IP)-classification of a product is normally executed according to set standards; globally it is controlled by IEC 60529, in Europe EN 60529, and it has also been converted into the Swedish Standard SS EN 60529. [25]

A products classification is defined as IPXY where X is a number (1-6) that stands for level of protection against intruding objects and Y is a number (1-8) that defines to which level the sensitive parts of the product are protected against water. [25]

Level of protection against intruding objects The level of protection ranges from a non-protected level which is denoted by zero up until the highest level of protection which compares to a dust tight sealage or protection. Determination of the parameter X is performed through the tests described in figure 2.9.

Table 2.7: UL 94 Flammability Ratings Description (UL94 general information)

Rating	Description
5VA	Burning stops within 60 seconds after five applications of five seconds each of a flame (larger than that used in Vertical Burn testing) to a test bar. Test specimens MAY NOT have a burn-through (no hole).
5VB	Burning stops within 60 seconds after five applications of five seconds each of a flame (larger than that used in Vertical Burn testing) to a test bar. Test specimens MAY HAVE a burn-through (a hole).
V-0	Burning stops within 10 seconds after two applications of ten seconds each of a flame to a test bar. NO flaming drips are allowed.
V-1	Burning stops within 60 seconds after two applications of ten seconds each of a flame to a test bar. NO flaming drips are allowed.
V-2	Burning stops within 60 seconds after two applications of ten seconds each of a flame to a test bar. Flaming drips ARE allowed.
H-B	Slow horizontal burning on a 3mm thick specimen with a burning rate less than 3"/min or stops burning before the 5" mark. H-B rated materials are considered "self-extinguishing".


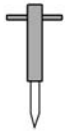




0	1	2	3	4	5	6
Non-protected	50 N sphere Ø 50 mm	10/30 N Test finger/sphere 12.5 mm	3 N rod Ø 2.5 mm	1 N wire Ø 1 mm	Dust-protected	Dust-tight Same test as 5
	 Sphere Ø 50 mm		 Ø 2.5 mm	 Ø 1 mm	 Max depression: 20 mbar Max extraction rate: 60 x volume/hour	 Max depression: 20 mbar Max extraction rate: 60 x volume/hour

Figure 2.9: Determination of level of protection against intruding objects (IP-klassning)

Level of protection against water Parameter Y of the IP-classification compares to the products degree of protection against water and range from zero which means non-protected to eight where the product can be continuously submerged. Tests performed to determine this part of the classification is illustrated in figure 2.10.

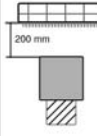
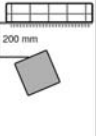


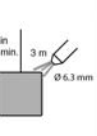
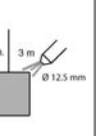
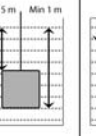
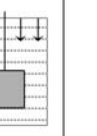
0	1	2	3	4	5	6	7	8
Non-protected	Water drop protected	Water drop protected inclination max 15°	Spraying water protected	Splashing water protected	Water jets protected	Powerful water jets protected	Water immersion protected	Continuous water immersion protected
	 200 mm	 200 mm			 Min 3 min, 3 m, Ø 6.3 mm	 Min 3 min, 3 m, Ø 12.5 mm	 Min 0.15 m, Min 1 m	

Figure 2.10: Determination of level of protection against water (IP-klassning)

3 Method

In the forthcoming section, the use of processes mentioned in section 2 and its application to this particular thesis is described. Further, tools for development and design which were used in this project are introduced, accompanied by an explanation of how their use have helped improving the end result.

3.1 Pre-Study

In order to achieve a good product, certain things must be known about the subject. The purpose of the product must be known, as well as its operating environment and how it is intended to be used. There are also large amounts of rules and legislations regarding industrial equipment. To find the necessary knowledge about these subjects, a pre-study was performed with literature studies, product benchmarking and consultations with experts in the field. These were performed in parallel, as insights gained in the consultations with experts led to new areas of literature being explored.

3.1.1 Literature Study

As the first phase of the project was based on an existing standard enclosure, the initial focus was placed on the user interface and the electronics packaging. These two areas turned out to be closely linked, as much of the literature that was found on electronics packaging also covered the ergonomics of the product in areas such as design guidelines for a keypad. The placement of electronics in a sealed enclosure in an industrial environment leads to a number of problems that need addressing such as heat management (section 2.2.2, electromagnetic compatibility (section 2.2.1) and other protection classifications. As the project progressed into its second phase, the research transcended to how an electronics enclosure could be optimised based on further research and the results of phase one.

Table 3.1: External search strings

Category	Value
User/usage	Operator, industry, measurement, control
Function name - Control	Terminal, panel, computer, control unit
Sub function 1 - Navigation	Keypad, keyboard, navigator, keys
Sub function 2 - Protection	Casing, housing, container, box, cover, shield, compartment, seal, enclosure, cabinet, chassis
Sub function 3 - Visualisation	Display, screen, monitor
Sub function 4 - Wall Mounting	Brackets, hanger, console, fixture
Material	Plastic, metal
Manufacturing method	Injection molding, vacuum forming, sheet metal
Joining	Snap joint, adhesive, screws, press stud, rivet weld

3.1.2 Product Benchmarking

In a technology-push project such as this, it was considered most important by the company board to reach the market with a product fast and prove its reliability and viability. Here, it meant relying on existing proven solutions for the enclosure of the electronics and not trying to revolutionise this field. To achieve this, the research involved searching patent databases and the Internet for competitive or similar products which could elevate the creativity and quality of the concept generation process. Searches were performed using a number of set parameters or strings in various categories which were combined to make the search as thorough as possible. These search strings are listed in table 3.1. Based on the gathered and organised information, a preliminary requirement specification was created for the different subsystems.

The project group also collected information at the Instrumenttekniska Föreningen (ITF) Automation fair, where retailers and manufacturers of similar products gather to network.

3.1.3 Consultation

The main portion of the information gathered during the project was found through open ended questions in informal interviews with specialists in the technical field, such as instrument technicians and purchasers of measuring equipment. These were of great help in understanding how products such as the one to be developed are used, what demands they impose on them and what is considered to be good and bad in their handling. Part of these interviews were performed in industrial environments where the product is to be used to facilitate understanding and creativity.

3.2 Product Development Process

In accordance with the theories posed by Ulrich and Eppinger in section 2.1.1 the development was initiated with a period of planning. The planning was done as thoroughly as possible for the entire extent of the project, therefore it was valid for phase one as well as phase two. Considering different approaches to Product Development, amongst other the ones described in section 2.1.1 to 2.1.3, one must be flexible when defining the approach so that it fits with present prerequisites. Therefore, in this project, it was chosen to follow Ulrich and Eppingers process model with influences from LPD (e.g. front loading the process and using a set-based approach with a cross-functional integration) and Agile Development (responsive approach to changing requirements to comply with the short amount of time). One difference that can be noted between the two phases that constitutes the project was that for phase one a standard enclosure was used due to the time constraint. This reduced the available design space and required some rationalisation in the development process. The pre-serial enclosure from phase one was therefore used for testing and refinement as input for phase two rather than being included in the first phase. As mentioned in section 1.5, production ramp-up was left out due to lack of time.

As mentioned in the previous section, plans were made for the entire project, making each phase one subproject. This led to the fact that two partly separated development processes were conducted. The components which were developed in the first phase were the front panel with its attached keypad and display together with development of a fixture for the display and PCB as well as implementation of a suitable connector interface.

3.2.1 Concept development

Following the five-step method described in section 2.1.1, the concept generation was started with identification of subproblems. This was done using common sense and pondering in a miniature workshop.

Based on the gathered and organised information, a preliminary requirement specification was set for the various subsystems. This specification was continuously revised as new information was added to the project. The development followed from the stated requirements, a number of guidelines to keep momentum and focus during the project.

- The terminal will be mountable on existing structures
- The terminal will withstand tough environments
- The terminal will house standard connectors for communication interfaces and power supply
- The terminal will be sealed from contaminating elements
- The terminal will be aesthetically appealing
- The terminal will elicit its company origin
- The terminal will be possible to install without exposing the internal components to the outside environment
- The terminal will facilitate the HMI
- The terminal will be able to hold the necessary equipment components
- The terminal will be operable with gloves
- The terminal interaction will be ergonomically designed
- The terminal will allow cable termination separated from internal equipment components

The next stage was to explore the concepts systematically. Several concepts picturing variants of the identified subsystems were generated during brainstorming sessions. Each conceptual solution was accompanied with a generic sketch to help mediate its characteristics. The session on each subsystem was limited to last for fifteen minutes and aimed at producing in total ten concepts on each sub solution. The concepts were then assessed based on the set requirements. Gathered knowledge was used as a first screening method where infeasible concepts or those who were in direct conflict with the specification were eliminated. Remaining concepts then entered the planned elimination phase which was performed with several selection matrices. Found concepts were cross-fertilised in morphological matrices to assure a full coverage of viable and promising solutions.

The final stage of the concept development phase was an evaluation where all aspects of the remaining concepts were considered. In total three full-system concepts were kept for further evaluation to maintain the set-based approach, which also meant staying flexible and avoiding possible restraints or traps in development.

3.2.2 System-level design

A more thorough product description was achieved in the system-level design. Discussions around the product structure facilitated communication between team members and division of work efforts since a more overall perception of the product was obtained. From this mapping process a geometric representation of the intended solution was created.

3.2.3 Detailed Design

In this part of the process the final geometric appearance of the product was defined and re-produced as a 3D-model (see section 3.3). The final specification of the manufacturing data was compiled with amongst other definition of materials and geometric tolerances. Based on delivered data a cost sheet was put together by suppliers. At this stage the two phases of the project differed to some extent since the delivery from the second phase was an alpha prototype.

3.2.4 Testing and refinement

As mentioned, testing was left out almost entirely in the first development phase. This was required due to the short amount of time but was motivated as legit due to the extensive use of standard components which already was specified according to certain classifications. However, the pre-serial enclosure required a close collaboration with people responsible for internal components such as PCB's. To verify component compatibility simpler forms of physical mock-ups were used.

3.3 Digital Prototyping and Design

For the purpose of visualisation and creation of manufacturing data a computer software for Computer Aided Design (CAD) was used. The software that was used, Catia V5, is developed by Dassault Systemes and is well known in todays industry. In the second phase the CAD was done using the software Inventor from Autodesk. This decision was taken in order to reach as high level of compatibility with the external design partner as possible.

At an early stage the software was used for mediating purpose with geometric representations together with more generic sketches produced in Autodesk Sketchbook Designer.

When the final solution was chosen, the detailed design was conducted with 3D-models of the product and drawings as outcome. To visualise the outcome of each phase, Catia's integrated module for realistic product renderings, Photo Studio, was used to communicate the progress and as presentative material in marketing purpose. The conceptual design from the second phase was assessed for its manufacturability, using a module integrated in Inventor for draft analysis, and an injection molding simulation was performed in Autodesk Moldflow to identify and evaluate possible defects at an early stage.

3.4 Cost Estimation

In phase one a total cost per unit was derived directly from invoices on ordered components from suppliers. In phase two a cost estimation was performed in the manner described in section 2.3.2 using the calculation software MATLAB. This covered the manufacturing costs of tools used for injection molding of the product developed in phase two.

4 Results

In this following sections results from each of the two phases are presented in the order of the executed stages used in the Product Development process.

4.1 Planning

At project initiation a comprehensive project plan was put together. Although the project was divided into two sub projects the planning described the entire process as thoroughly as possible. But as mentioned earlier a constant revision was required in order to adapt to changed conditions. A general breakdown which presents major events and milestones is presented in figure 4.1

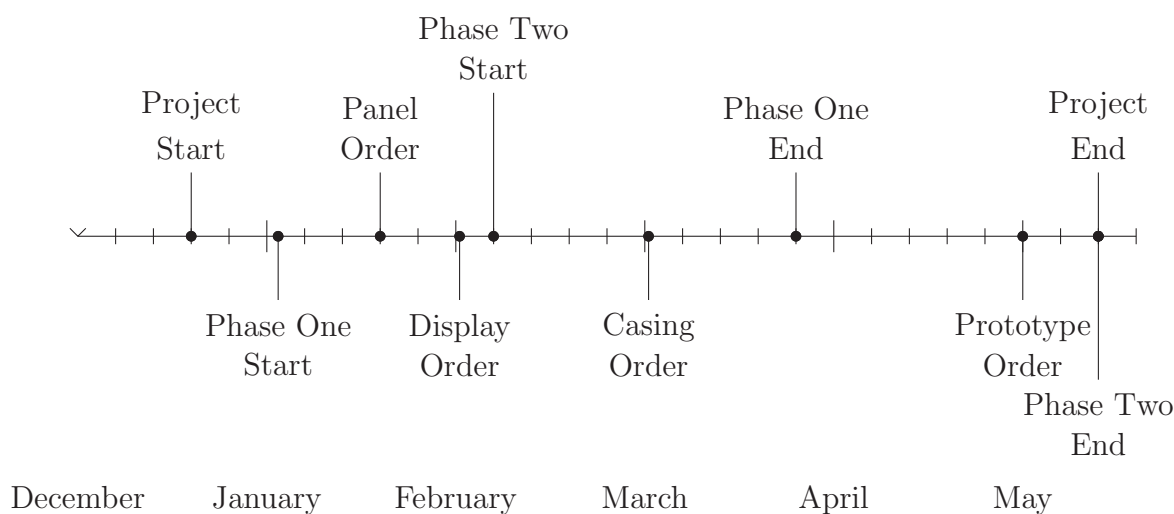


Figure 4.1: Project Plan with Major Events

The comprehensive plan is presented as a Gantt chart in appendix A.

4.2 Phase One – Pre-Serial Enclosure

This section summarises actions taken and occurred events during the first phase of development with gathered material and produced documentation.

4.2.1 Concept Development

To stimulate and initiate the concept development a mood board was created. This was intended to elicit anticipated product conception and to bring forward important design aspects such as the level of protection required for the harsh environments. This mood board can be seen in appendix B. For clarification of product architecture as well as communication between group members and project contributors of the same, an illustrative description of the system was put together which can be seen in figure 4.2.

Next, requirements concerning the product were gathered into a specification, a document which has been an object for a continuous revision. These were posed by different stakeholders in the project, both external such as customers and instrument technicians, as well as internal ones in Acosense. The requirements were sorted into their respective category.

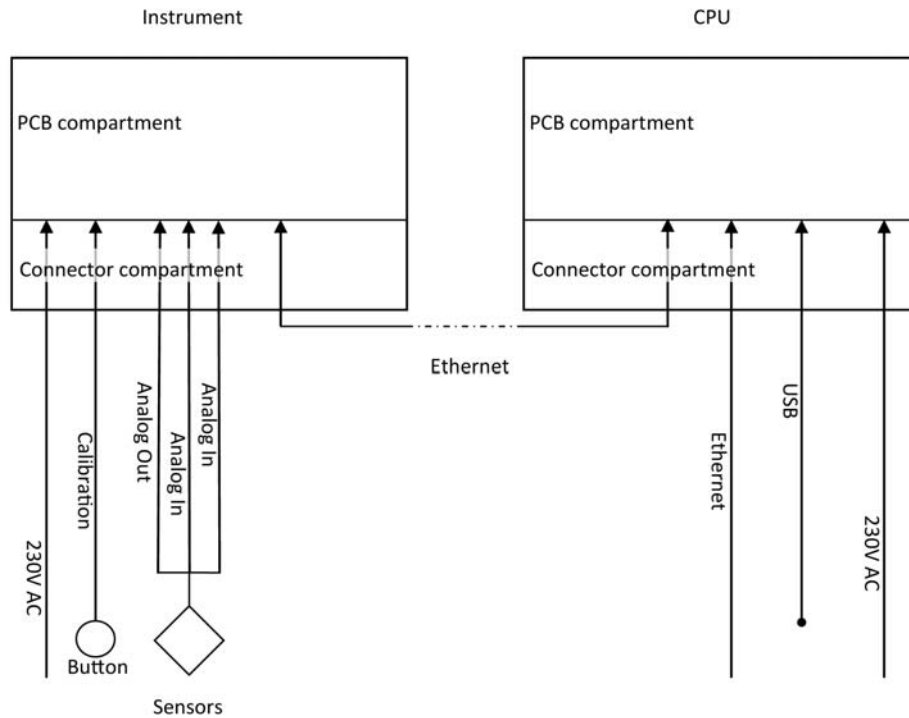


Figure 4.2: System architecture

Appearance: The appearance requirements were posed by Acosense AB to provide the product with an appealing design, expressing robustness and innovation.

Protection: The requirements on the protection classifications were posed by customers, as they are the specifications they require when purchasing products. IP was a general demand in the industry together with EMI, as these are required for the product to work in the intended environment. The thermal range requirements were based on the high temperatures in some applications and that not all electronics are able to comply with such specifications. The ATEX requirement must be fulfilled for the product to be installed in certain zones of the industries (section 2.4.1) and if the product is to be applied in the mining industry. A general approach that was used when formulating the requirements was that it would be better to strive for the highest classifications on all points so that it did not limit the application of the technology in new fields in the future.

Physical constraints: When these kinds of products are installed in the industry, space is usually made for them by setting up a new cable ladder or placing the product on a wall or in an installation cabinet. As cables are always routed from the ceiling in an industrial environment such as this, there is always room in the vertical plane meaning height is not a limit as long as it is within reasonable limits. This is not necessarily the case for the depth and the width of the product. To ensure that an improvement is actually made on the product size, a volume constraint was created as it might otherwise be difficult to evaluate it when one or two dimension decrease and another increases.

Interfaces: The constraints for installation were set up to facilitate the work of the instrument technicians, as they were the ones interacting the most with the product and therefore the ones who might consider it good or bad without concern to the technology inside. The connector type compatibility was mostly regarding the cable gland types that were used.

Production: The demands on producibility were posed by Acosense to maintain a low production cost and thereby increased margins. The intention was not that the enclosure for the electronics should take up a considerable part of the product cost, and keeping the part count down and using standard components as far as possible was considered to be a good solution to this problem.

An extract from the specification is presented in table 4.1 while the complete specification can be found in appendix C. In the table Subj. is short for Subjective and rated from one (being the lowest) to five (being the highest).

The information searches performed according to the systematic approach described in section 3.2 resulted in a vast amount of inspiration and memorable solutions. The gathered data made the foundation of the proceedings of the concept development.

Based on the above mentioned specifications and gathered information brainstorming sessions took place. Conceptual ideas were generated for each identified subsystem that was covered in the first development phase: numeric key pad, navigation key pad and panel (see figure 4.3). As ideas were generated, the various subsystems were assessed in evaluation matrices (see appendix D for matrices with illustrated concepts). Different solutions were then combined in a morphological matrix. As the theories implies (section 2.1.1), the sessions were kept in an open minded manner which also allows for ideas of a more visionary kind. These ideas were not entirely discarded since solutions that seemed unfeasible at first could provide value at a later stage.



Figure 4.3: Panel Print Concepts

Assessment of the generated keypad concepts were based on ergonomic considerations as described in section 2.3.1 as well as their visual appearance

Table 4.1: Extract from Requirement Specification

Category	Need	Metric	Unit	Value
Appearance	Appealing design	Aesthetic and robust feeling	Subj.	>3
Protection	Protected from water and dust	IP	Class	68
	Safe to use in explosive environments	ATEX	Category	1
	Withstand internal thermal loads	Thermal range	°C	-30 – 85
	Withstand external thermal loads	Thermal range	°C	-30 – 60
	Minimum of EMI	EMC	Binary	Non-emissive
	Non-flammable	Standard	UL 94	V-0
Physical Constraints	Requires a minimum of space	Volume	dm ³	19
	Operable with gloves	DFE	Subj.	>4
Interfaces	Mountable on existing structure	Compatibility	List	Cable ladder Wall
	Installable with standard tools	Standard tools	List	Screwdriver Wrench
	Mountable without PCB exposure	External fixtures	Binary	Yes
	Signals I/O	Connector types	List	Main unit Power 2xEthernet Instrument unit Power Ethernet 2xAnalog I 1xAnalog O Calibration
Production	Easy to assemble	DFA	Subj.	>4
	Easy to disassemble	Fasteners	Type	Phillips screws

Resulting from the concept generation, three alternatives were developed to an extent sufficient for presenting it to members of the board who granted a final decision. The three remaining complete alternatives were 'Honey comb', 'Bolt' and 'Cross-hair' where 'Bolt' was considered the prime alternative and hence qualified for further design (see figure 4.4).

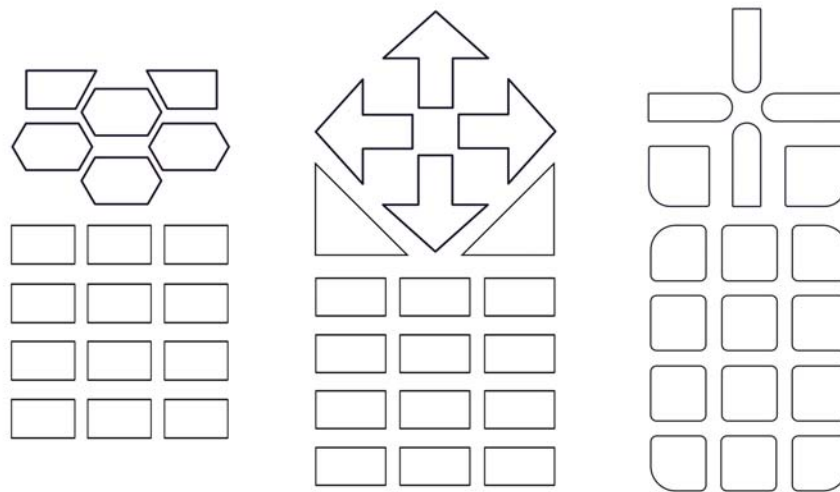


Figure 4.4: Concepts qualified for final decision

4.2.2 System-Level Design

Design was approached at a systematic level where required components in excess of those covered in the preceding phase were identified. To assure the coverage of the first phase and to prepare for the forthcoming development, communication with supplier and product data sheet from manufacturer were used to determine included components that were required to comply with stated requirements.

Other than parts belonging to the enclosures, several additional components were found and considered as standard e.g. cable glands and fasteners. It was also decided that a mounting solution was required for attaching the display to the panel and also to provide possibility of attaching the PCB's within the enclosure. This was decided to be developed in close collaboration with the suppliers of the internal electronics at the stage of detailed design to assure full compatibility.

4.2.3 Detailed Design

In the detailed design stage a focus was primarily put on the critical components, i.e. the panel due to anticipated long delivery times. Its design consisted of two main components: front and keypad.

Front Design Based on the conceptual idea of the panel layout a final design was initiated in consultation with the company's communications manager. It involved a mechanical design of the front which fitted into the chosen enclosure and finding an aesthetically appealing print design. In figure 4.5 the final panel concept is presented. This is also described thoroughly as a mechanical drawing in appendix E.

The theories on DFE (section 2.3.1) were taken into account at an early stage. Here follows a number of design features which characterises the final front design.



Figure 4.5: Final Panel Design

- Keypad located to the right to enable operation without blocking the sight for a majority of the population which is right-handed.
- Standard sized display viewing area commonly used in industrial applications, 5.7 inches in 4:3 format.
- Print layout designed in accordance with the company's graphical profile and supplied with a logotype in order to elicit brand and product recognition.
- The front is matte, excluding the display viewing area which is glossy. This decreases the perceived loss in quality in case of defects or wear.
- Polycarbonate was chosen as front material due to its thermal characteristics (table 2.1) which allows for usage in specified environments without an increased rate of deterioration.

Keypad Design In accordance with the theories described in section 2.3.1 and on the basis of expert consultation the keypad was developed.

To implement desired functionality when operating the keypad a keyboard matrix describing its electronic circuits was composed. The 17 buttons required a 5x5-matrix leaving one of the poles out of use. The circuit diagram is presented with the rest of the manufacturing documentation provided to the supplier in appendix E.

Characteristic for the keypad and aspects considered within the design space were among others those listed below. All of these are however not visible in the figure.

- Adequate button spacing and size to allow for operation with gloves.
- Buttons of metal domes type which through resistance provides an haptic and audible feedback at pressure.
- Numbers printed with contrast to background colours for high degree of visibility in different lighting conditions.
- Stroke of the buttons chosen to enhance the haptic experience without inheriting a risk of accidental activation.

- A clearly recognisable design of navigation buttons in the shape of arrows enhances use by intuition. The design is robust and is guaranteed to communicate its purpose during the products entire life cycle.
- Keys arranged as a telephone keyset, an arrangement well known to operators and used also in everyday life.
- Buttons made in silicone which is a material applicable in harsh industrial environments.

Display and PCB Fixture Design Design of a fixture which holds the display in place as well as provides a mounting possibility for PCB's was carried out in close collaboration with the PCB supplier. The available space was limited due to the spread of the display on the panel. The final solution can be seen in figure 4.6.

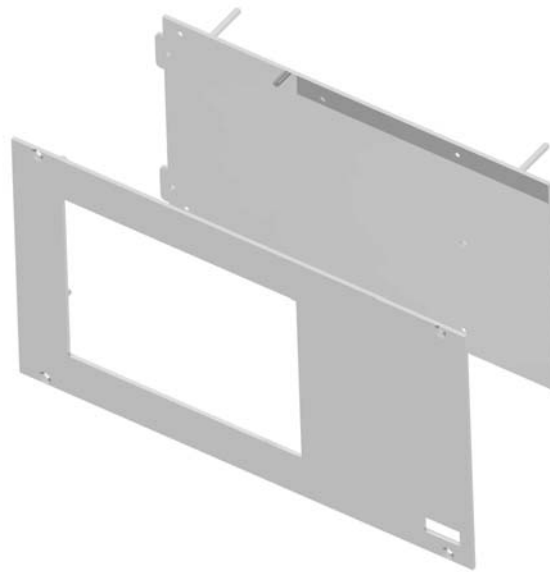


Figure 4.6: Fixture Design

Typical design features for the fixtures are as follow.

- Simple design in sheet metal work completed with standard components for fasteners.
- Provides possibility to mount the panel without visible ingression which could inflict an aesthetic regression.
- The sandwich design fulfills two requirements, it holds the display as well as provides a possibility to mount the PCB.
- Dimensions set for hole diameters to avoid tolerance stack-up.

Based on generic drawings provided by the supplier a digital mock-up of the enclosure, which in this phase was purchased off the shelf, was created using CAD. Together with the developed physical interfaces presented above this enabled an overall rendering which provided a feeling of the complete product. This was used for internal project communication with stakeholders and potential customers. The rendering is presented in figure 4.7.

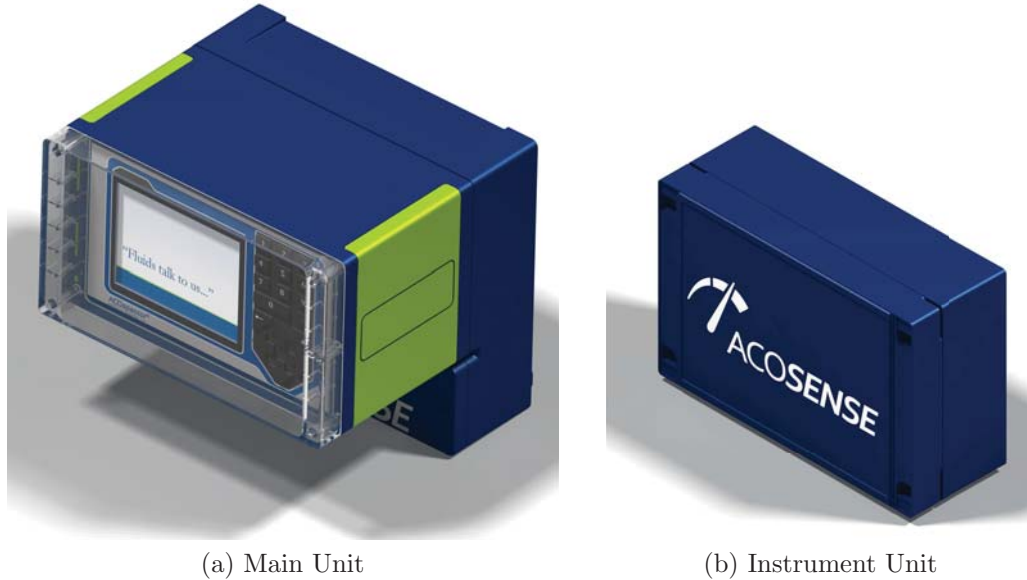


Figure 4.7: Renderings of concept developed in phase one

4.2.4 Testing and Refinement

Development involved a continuous revision of the chosen concept as other parts of the product evolved. After finalising design of the pre-serial enclosure it was assembled and evaluated to form the basis of the second phase of the project.

Thermal Considerations Thermal performance of the chosen concept was evaluated using the equations from section 2.2.2. The requirements stated that the product was supposed to function properly in a temperature span from -30°C to 60°C . The defined and calculated values needed to find the critical internal temperature were as follows from equation (2.2).

$$U = \begin{bmatrix} \alpha_1 = 7 \frac{\text{W}}{\text{m}^2\text{K}} \\ \alpha_2 = 0 \\ d = 0.002\text{m} \\ \lambda = 0.17 \frac{\text{W}}{\text{mK}} \end{bmatrix} \approx 6.47 \frac{\text{W}}{\text{m}^2\text{K}} \quad (4.1)$$

$$A \approx 0.36 \quad (4.2)$$

Results from equation (4.1) and (4.2) implies given energy dissipated from internal components, $\dot{Q}_{ekv} = 50\text{W}$, and a critical surrounding temperature of $t_o = 60^{\circ}\text{C}$ (values estimated with a safety factor)

$$t_r = \frac{50}{6.47 * 0.36} + 60 \approx 81.47^{\circ}\text{C} \quad (4.3)$$

This derived temperature can then be used to determine the highest junction temperature in operation which was described in equation (4.4). Specifications given by the manufacturer of the processing units gives the dissipated energy, $P_D = 5\text{W}$. Knowing the ambient temperature and using tabulated values for the thermal resistances; $\theta_{jc} = 0.21 \frac{^{\circ}\text{C}}{\text{W}}$ and $\theta_{ja} = 1.14 \frac{^{\circ}\text{C}}{\text{W}}$ Hence, the anticipated junction temperature would be

$$T_j = 81.47 + [(0.21 + 1.14) * 5] \approx 88.22^\circ C \quad (4.4)$$

and this value should be compared to data provided by the circuitry manufacturer.

4.2.5 Production Ramp-Up

The pre-serial enclosure developed in phase one was intended for an in-house production of 20 units. Due to the low production volume, this was done through manual labor from assembly to spray coating the product in colors according with the company's graphical profile. A photograph showing the final product can be seen in figure 4.8.

4.2.6 Evaluation of Phase One

To use the standard enclosures as a benchmark for improvements in the second phase, an analysis of their pros and cons was needed. This was performed by systematically evaluating all of their features and comparing them to the requirement specification, as well as to the input received from consultations. This is presented in the list below.

Physical dimensions (WxDxH):

- Main Unit: 264x241.5x230 mm
- Instrument Unit: 240x90x160 mm

Mounting:

- Both enclosures are mounted using separate components, the Main unit using a slide-in system and the Instrument unit screwed on mounting tabs.

Number of parts:

- Main unit: 11 (Including PCB fixture and mounting parts)
- Instrument unit: 10 (Including PCB fixture and mounting parts)

Usability:

- Left handed users risk covering the display when using the keypad on the main unit.
- Connection compartment cover on the main unit held by captive screws.

Protection:

- Instrument unit lacking separate connection compartment.
- Main unit lacking separating wall between connection compartment and main compartment.
- Panel protected by hinged hatch on main unit.
- IP65 classification for both enclosures.
- EMC coating optional from supplier.
- ATEX classification not available.
- No additional parts for heat dissipation apart from plastic enclosure walls.

Visual appearance:

- Conservative, stereotypical industrial looks.



(a) Main Unit



(b) Instrument Unit

Figure 4.8: Photographs of the demonstrator system

4.3 Phase Two – Customised Enclosure

In the following section, the results from the development work of the customised enclosure system is presented.

4.3.1 Concept Development

As the product generated in the second phase of the project had the same requirements posed on it as the pre-serial enclosure, the aim was to find areas of potential improvement and find where the customised enclosure might provide benefits for the customer.

Following the same methodology as in the first phase of the project, the requirement specification was studied and the product broken down into sub-systems aiming to fulfill different requirements. These were chosen to be compartment setup, panel protection, enclosure sealing and mounting solution. Conceptual ideas for technical solutions to these sub-systems were generated in brain storming sessions and through consultation with experts in the field. The work was focused on the main unit, as it has all the features of the instrument unit as well as some unique ones. Sketches and descriptions from these sessions can be found in appendix F. By using a morphological matrix, these sub-systems were combined into general concepts for the complete system, which were then evaluated through the use of selection matrices (section 2.1.1) and further consultations.

The concepts that were found to be the most promising and selected for further development can be seen in figure 4.9.

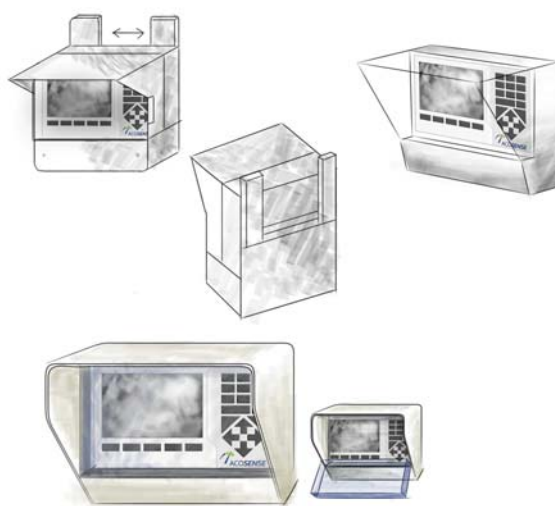


Figure 4.9: Principal concept sketches

Cubic

- Compartment setup: 'Wall-E', a compartment wall fixed into the structure of the enclosure.
- Panel protection: 'The Cap'N', a hatch with an integrated protective visor.
- Enclosure sealing: 'O-ring', a sealing profile between the different parts of the enclosure.
- Mounting: 'The Hangman', an external mounting plate with an integrated hook-and-hole interface.

ModBox

- Compartment setup: 'None', the use of external connectors eliminate the need of a separate termination compartment.
- Panel protection: 'Combo', a combination of an integrated protective visor in the enclosure design and a transparent hatch covering the panel.
- Enclosure sealing: 'O-ring' (for description, see above).
- Mounting: 'Snappy', an external mounting plate with an integrated snap-fit interface.

KiWi

- Compartment setup: 'Wall-E' (for description, see above).
- Panel protection: 'Combo' (for description, see above).
- Enclosure sealing: 'O-ring' (for description, see above).
- Mounting: 'Bird's nest', mounting holes integrated in the enclosure design.

4.3.2 System-Level Design

A general system-level evaluation was performed on the three concepts selected for further development from the concept phase to in further detail define major subsystems and interfaces and study the concepts feasibility. When studying the 'ModBox' features closer, it was found that external connectors with a sufficient protection class was difficult and expensive to obtain, and that the customers were not especially fond of this solution as connectors are generally used for products that are moved frequently, something the product is not intended to support. Since the rest of the 'ModBox' concept was similar to the 'KiWi' concept, it was not pursued further as a complete concept, but rather only as an alternative for the mounting solution.

The customer feedback differed on whether or not to have a protective visor, therefore it was decided to leave the alternative open but not integrate it into the enclosure or hatch design. This is due to that the main unit could be located in mounting cabinets together with other similar equipment, where a visor might get in the way, whereas on the other hand it might be useful if the product is mounted outside in sunlight, in places with much dripping.

At this point, it could be seen that the difference between the three concepts were merely the mounting solution and it was decided that in order for the customers to be able to mount the products in the manner they usually do, the 'Bird's nest' solution was to be pursued as this is the closest thing to an industry standard. When comparing the evolved concept to similar products in the industry and discussing its features with instrument technicians and customers, it was found that it was possible to achieve an adequate protection class of the main unit without utilising the carry-over hatch from the standard enclosure. This was due to change in product structure from the beginning of phase one. This would mean a reduction in size as well as further advantages when placing the main unit in installation cabinets, as the open hatch does not have to be considered when mounting the equipment in proximity to other products. The possibility was confirmed in discussions with design consultants and would be carried out by designing the panel so that it provides more ingress protection and is easier to clean if it is soiled, thereby reducing the product complexity by integrating more functions into existing structures and eliminating parts.

As the technical concept was evolved and verified by customers and experts in the field, the project group with support from the company felt confident to bring in an industrial

designer to provide support with the visual appearance of the product. This was considered important to aid the marketability of the product by providing it with a feeling of robustness and an expression of the cutting edge technology within. The final result from this session is seen in figure 4.10.

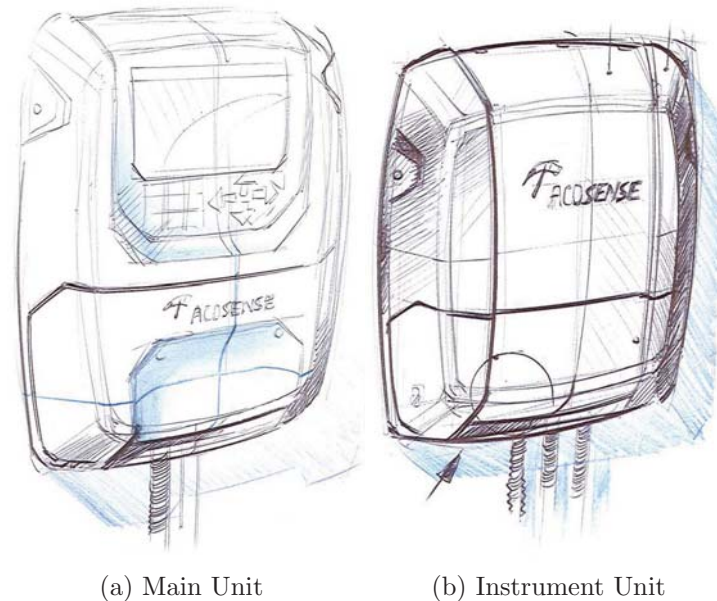


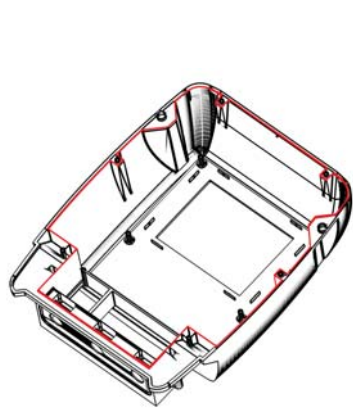
Figure 4.10: Final conceptual sketch of version 2

Having gathered enough material to proceed into detailed design of the product, a final review of the design features was made to assure that all requirements (see appendix C) were covered. An evaluation of these features (figure 4.11) was performed during the testing and refinement to ensure that the requirements were met to specification.

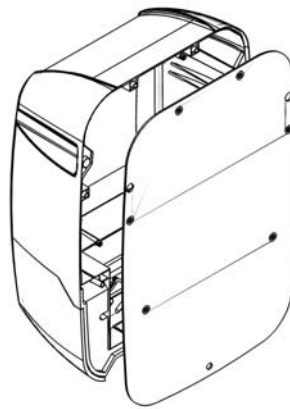
- Ingress protection is provided by an unbroken edge pressed against a sealing profile combined with a panel with sufficient area for adhesion (figure 4.11a).
- Heat generated by the inner components is lead off by the utilisation of a metal back plate for the enclosure (figure 4.11b).
- Mounting on existing structures with standard tools is facilitated by utilising the same type of mounting as similar products in the industry (figure 4.11c).
- Mounting without exposure of sensitive components is made possible by a connection compartment sealed from the main compartment (figure 4.11d).
- Captive screws holding the connection compartment cover facilitate assembly and installation (figure 4.11e).
- An appealing and robust feeling is achieved by using a design language with large radii and divergent lines (figure 4.11f).

4.3.3 Detailed Design

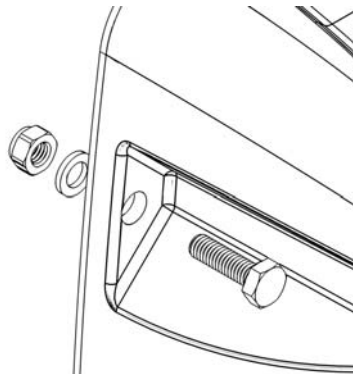
Detail design work was performed in previously mentioned 3D CAD environment (section 3.3) to accurately model features and geometries for evaluation.



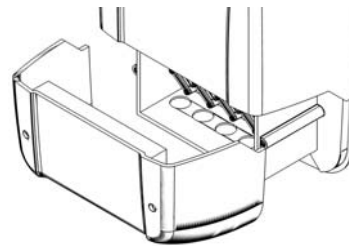
(a) Unbroken sealing edge



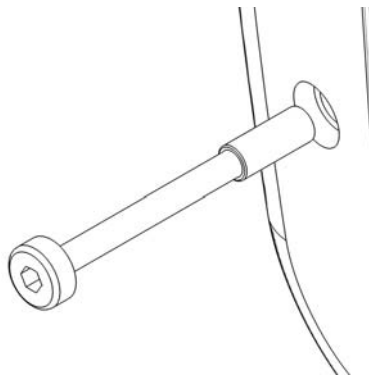
(b) Heat-dissipating metal backpiece



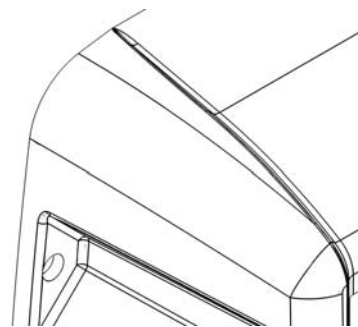
(c) Standard mounting solution



(d) Separate connection compartment



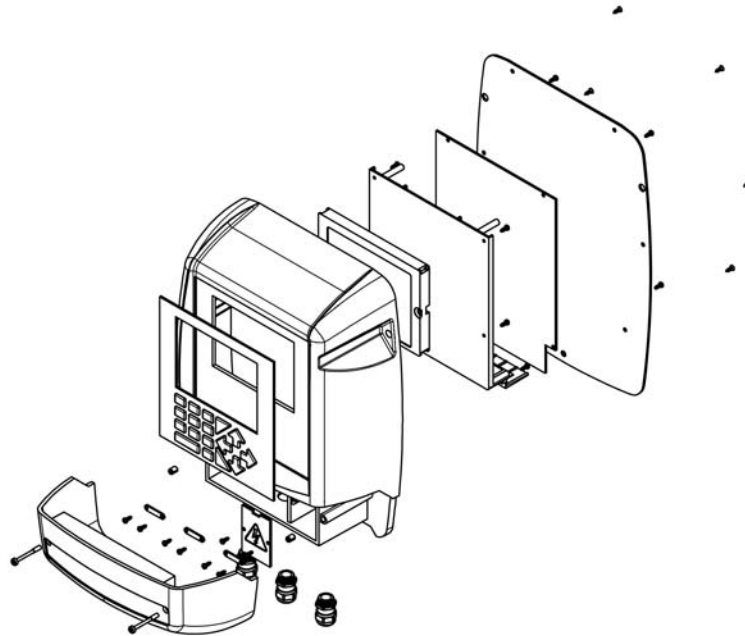
(e) Captive screws



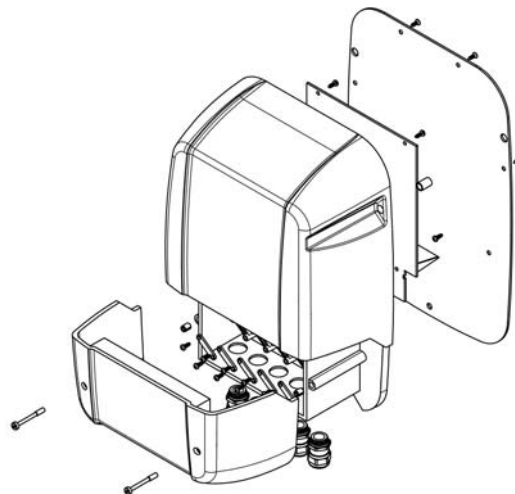
(f) Large radii and divergent lines

Figure 4.11: Illustrated features of version 2

The main unit consist of five components; a back piece made from acid-proof stainless steel, a front piece, a connection compartment cover, a fixture with integrated separator wall and a cover for the high voltage compartment all which are made from injection molding. The instrument unit has corresponding components apart from the fixture which is replaced by a separator wall and the high voltage compartment cover which is not required. The main unit also features the user interface panel holding the display and keypad which together with the instrument unit is seen in figure 4.12.



(a) Main unit exploded view



(b) Instrument unit exploded view

Figure 4.12: Exploded line renderings

The material chosen to base design work on was PA66 (section 2.3.2). This preliminary approach to material selection was performed on the basis of the mentioned polymers properties which are beneficial in consideration of ATEX classification. Screws and metal inserts were chosen from standard components to improve producibility and reduce cost.

All the feature intelligence was implemented into the front compartment, allowing the back piece to be made from metal as it only needs to hold the mounting and assembly

holes as well as an adhesive sealing profile. The edge pushing against the sealing profile was created by sweeping a profile along the seal path. This edge is offset 2 mm from the back piece to make room for e.g. a rubber gasket as seen in figure 4.13.

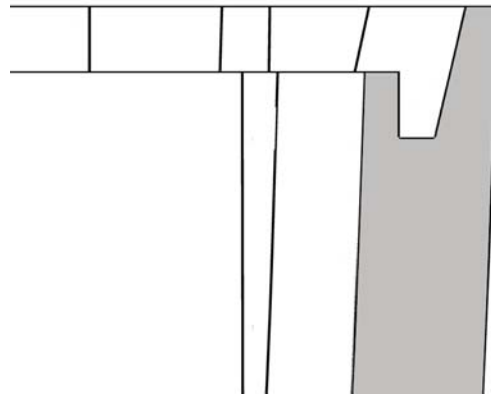


Figure 4.13: Close-up of sealing edge cross section

All mounting and assembly holes are placed on bosses outside of the sealed perimeter so that the screw holes do not need to be sealed, see figure 4.14.

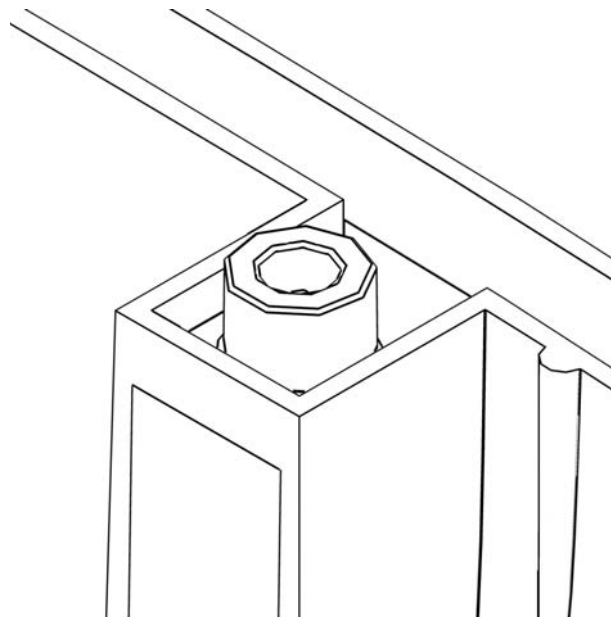


Figure 4.14: Sealing profile with assembly bosses

The cut-away for the mounting holes is designed so that the mounting profile does not extend from the enclosure while still being reachable with standard tools such as a manual or an electric screwdriver. The mounting holes on the front have metal inserts to relieve the strain on the plastic to prevent cracking in the event of the installation worker over-tightening the screws (figure 4.15).

There are threaded metal inserts in the mounting structure for the connection compartment cover (see figure 4.16) to prevent wear in the plastic when it is removed and

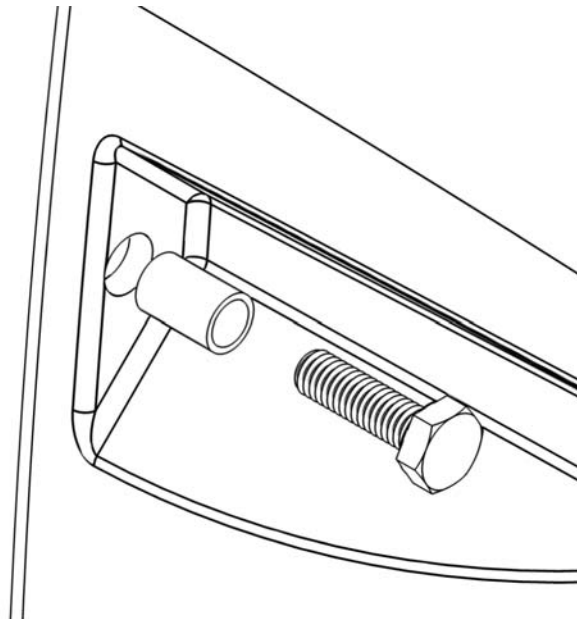


Figure 4.15: Metal inserts in mounting holes

put back on, as well as relieve strain in the event of over tightening (section 2.3.2). This was not deemed to be necessary on the assembly holes, as the product was intended to be assembled in house at the manufacturer allowing better control over tightening torques.

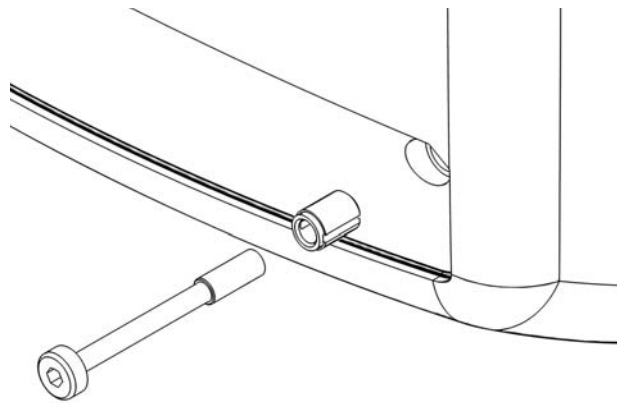


Figure 4.16: Metal inserts in cover mount

In the main unit, the display is positioned with flanges in the corners and held in place by a fixture. This fixture is mounted to six bosses in the front, around four of which material is removed in a 'ditch' to reduce the risk of sink marks in the outer surface (2.3.2). This is not as sensitive as the front surface of the instrument unit since the panel will be covering it on the main unit, but it still needs to be smooth to allow the adhesive to fasten properly. The PCB's are mounted onto bosses on the fixture to reduce the number of features in the front surface (see figure 4.17). The fixture is shaped in such a way that it leads off from the PCB towards the back piece at the start of the connection compartment, thus creating one half of the separating wall between the two compartments. The other half is integrated into the front and holds the last set of bosses for mounting the fixture (see figure 4.19).

In the instrument unit, the PCB's are mounted on fixed bosses, one set of which are designed with a side pull to reduce the risk of sink marks in the front surface of the

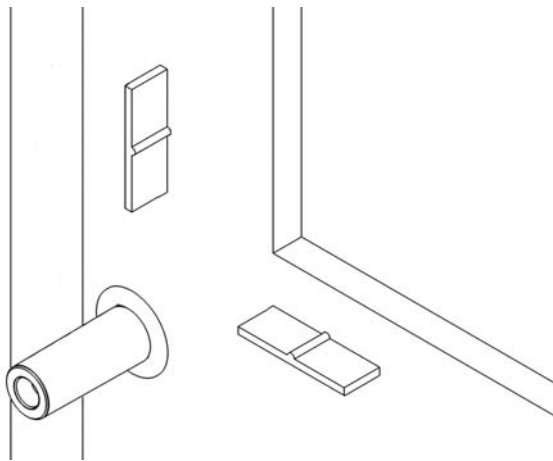


Figure 4.17: Fixture and display locators

enclosure (see figure 4.18). The second set of PCB bosses have been incorporated into the wall separating the PCB compartment from the connection compartment (see figure 4.19).

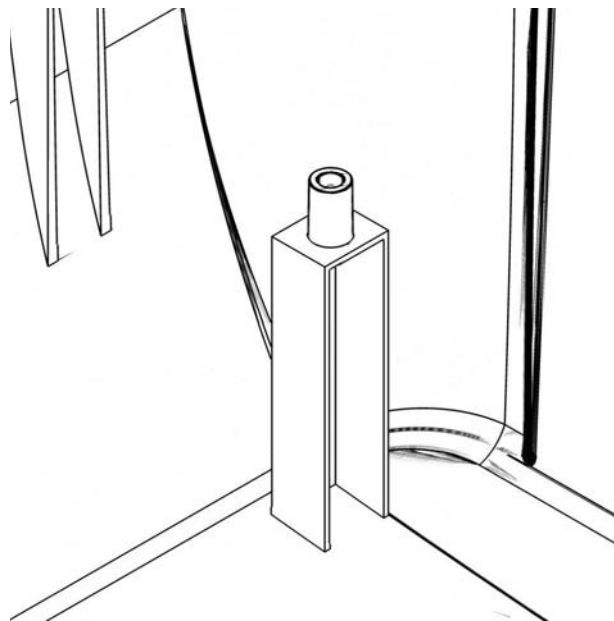


Figure 4.18: Close-up of PCB boss

The connection compartment has integrated mounts for strain relief clamps at the holes for cable glands (see figure 4.20). In the main unit, there is also a fixed wall and a cover mounted with screws separating the high voltage parts of the PCB from the low voltage. This is to allow people without high voltage qualifications to install and perform maintenance on the data handling connections on the PCB.

The cutaway for the compartment cover is angled more than just the draft angle to guide the cover in place even if it is a little misaligned after manufacturing. The sealing edge of the connection compartment holds a sealing profile similar to the one on the back piece and the sealing edge on the cover is also offset 2 mm. The bottom of the compartment cover has a cutaway to give room for the cable glands when attached to the front (see figure 4.21).

To aid manufacturing of the product, some general guidelines described in section 2.3.2 have been applied to all features in the two plastic parts:

- An even material thickness on the shell to prevent skewing due to different cooling

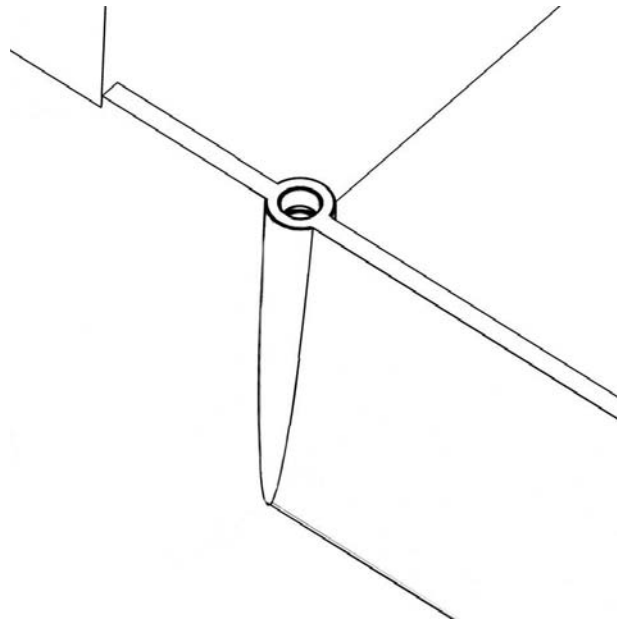


Figure 4.19: Close-up of separator wall with boss

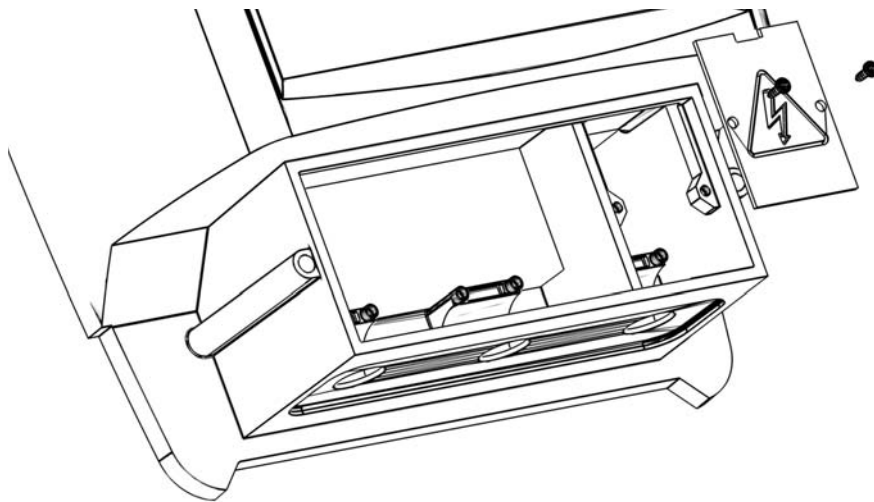


Figure 4.20: Connection compartment

times.

- A minimum of 0.5 degree draft angle to reduce the friction between material and tool.
- As few and as small all-flat surfaces as possible to make defects less noticeable and strengthen the parts.
- Thickness of ribs and bosses no more than 75% of the nominal material thickness to prevent sink marks.
- Ribs and bosses placed on non-sensitive surfaces to avoid visible defects.
- Material no thinner than 1 mm to facilitate mold filling.
- Ejector pins have been placed on the thin profiles to avoid problems when ejecting the part from the mold.

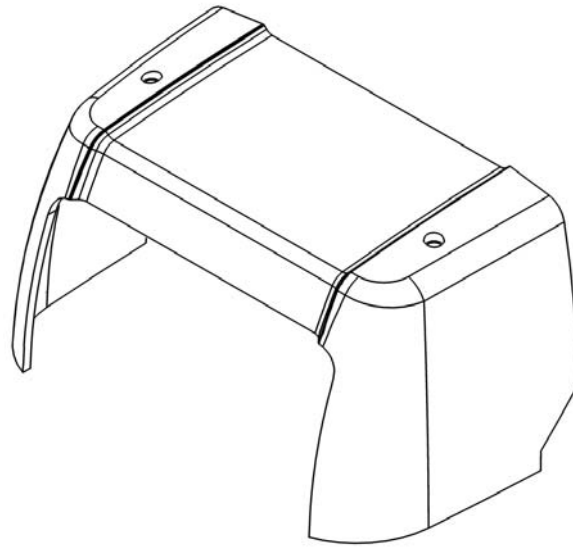


Figure 4.21: Connection compartment cover

For general geometrical descriptions and intended PCB sizes, one is referred to appendix G. The drawings are only meant as illustrations and not manufacturing documentation as the concepts were still in an early stage of development.

To visualise the final outcome of the project figure 4.22a and figure 4.22b depicts rendered models of the expected product whereas figure 4.23 presents a photograph of the SLS-prototype.

4.3.4 Testing and Refinement

Testing of the product was performed on both a virtual model and a physical prototype. The virtual model was used to analyse manufacturability by performing a draft analysis highlighting where problems might arise when the mold is parted.

Injection Molding Analysis From the analysis of the cover we can see that the frozen layer fraction at the end of the fill is high in the sealing profile of the connection compartment (figure 4.24a). The frozen layer fraction is the thickness of the frozen layer during fill, and a higher value indicates a thicker frozen layer (thinner flow layer) meaning increased flow resistance, i.e. making the tool more difficult to fill. In the fill time study (figure 4.24b), the different colors indicate at what time the mold was filled, where areas with the same color are filled at the same time.

The fill time analysis on the main unit front (figure 4.24c) shows that with the inlet placed at the bottom of the screen, there is a risk of a visible weld line on the top of the product, as the two masses of material meet there. We can also see that the divider for the high voltage compartment acts as a conductor for the material, allowing it to flow easier into that part of the mold compared to the side without it.

Interference analyses were performed on both the virtual assembly and the physical prototype to ensure that the product can be produced and assembled as intended.

Evaluation compared to the standard enclosure To ensure that improvements had been made compared to the standard enclosures used in phase one, an evaluation was



(a) Main Unit



(b) Instrument Unit

Figure 4.22: Renderings of concept developed in phase two



(a) Main unit with cover



(b) Main unit without cover



(c) Instrument unit with cover



(d) Instrument unit without cover

Figure 4.23: Photographs of the SLS-prototype

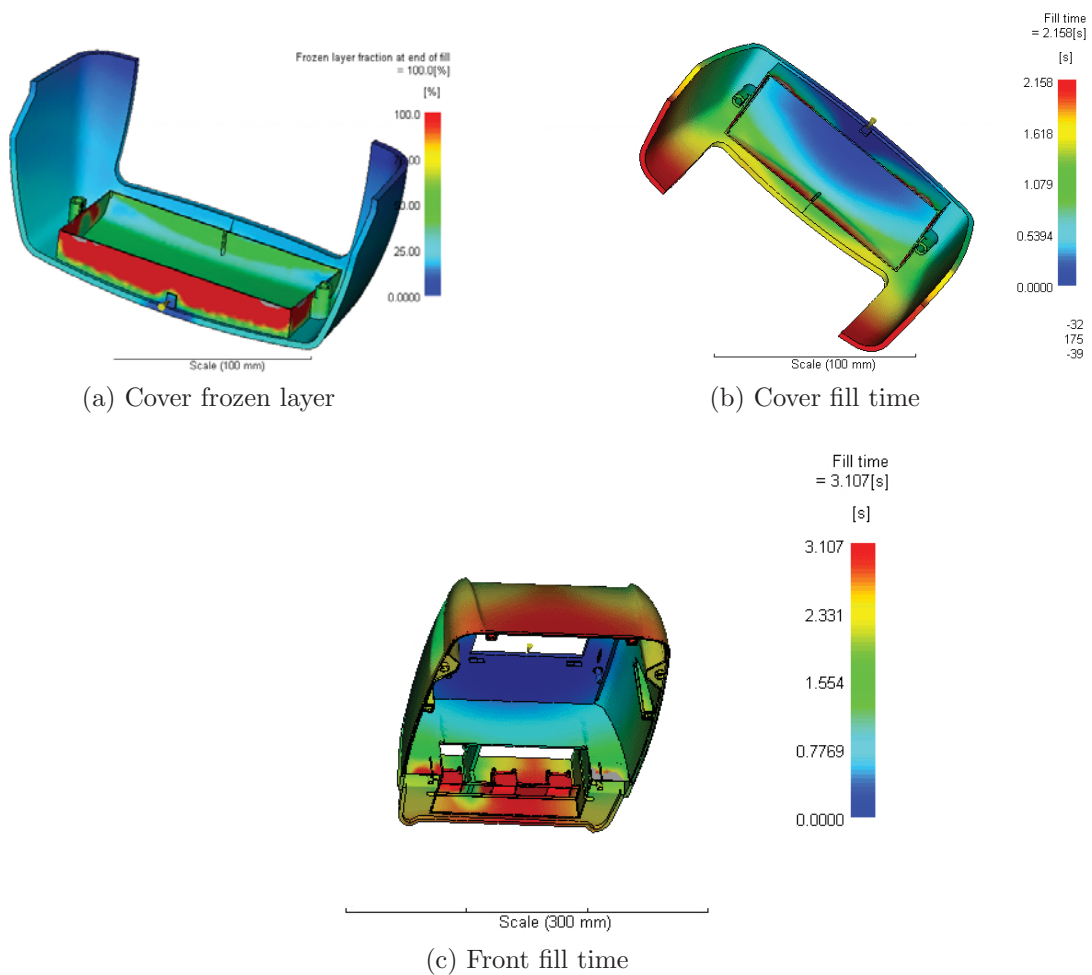


Figure 4.24: Moldflow analyses

performed of the digital and physical models of the products. This was then compared to the corresponding list from phase one.

Physical dimensions (WxDxH):

- Main Unit: 245x120x330 mm
- Instrument Unit: 210x110x300 mm

Mounting:

- Both enclosures have integrated mounting solutions.

Number of parts:

- Main unit: 5
- Instrument unit: 4

Usability:

- Keypad located under display facilitates use for left handed people.
- Connection compartment held by captive screws.
- No hatch on main unit facilitates use in installation cabinets.

Protection:

- Sealed connection compartment on both units.
- IP68 (to be verified) classification for both units.
- EMC coating (to be verified).
- ATEX classification (to be verified).
- Back pieces in metal for improved heat dissipation.

Visual appearance:

- Creative, design language expressing robustness and innovativeness.

4.3.5 Manufacturing Cost Estimation

Based on the method described in section 2.3.2 a preliminary cost estimation was put together. The cost for manufacturing required tools for each of the components intended for injection molding was derived and assessed. Based on component tool cost the accumulated value for main unit and instrument unit respectively was found. Tool costs in Swedish Kronor (SEK) is presented in table 4.2.

Table 4.2: Tool manufacturing cost, SEK

Main Unit	Cost
Front	260,000
Cover	60,000
Fixture	100,000
Voltage compartment cover	15,000
Total:	435,000
Instrument Unit	
Front	210,000
Cover	45,000
Separator	45,000
Total:	300,000

5 Discussion

One of the main challenges of this project was the changes in product structure and requirements that have taken place since the start. In the beginning, the system consisted of one enclosure for the entire system that was intended to be placed in direct vicinity to the measuring point in the factories, since the cost of the cables connecting it to the accelerometers was very high. As the development of the internal components proceeded, it became clear that the standard enclosure the project's first phase was based around would not be enough to fit them all. This led to the addition of one more enclosure, both of them still mounted at the measuring site. Further development of the technology revealed that it would be possible to separate the electronics handling the analog signal and the ones performing the calculations, and connect the two enclosures via an ordinary Ethernet cable. This spawned the idea of an instrument unit and a main unit, where only the instrument would have to be placed near the measuring site and the main unit could be placed in a more protected location, e.g. in an installation cabinet. It was still important to keep the protection class of the main unit as the product still is intended to be usable by customers that do not use such cabinets. The fact that the instrument unit would not need to handle any human interaction other than installation and maintenance made it possible to make it more robust by eliminating some of the sensitive components as well as the holes in the enclosure for the display and the keypad. As this became clear in the end of the first phase of the project, it provided good material for the further development of the product as well as a clear product structure.

A constant source of frustration and external uncertainties was the delivery and lead times of components and meetings with some external parties. An example of this was the panels, which were ordered in the end of January with an expected delivery time of four to six weeks, but arrived in the second half of April. Not only the delayed deliveries were a cause of problems, but also the unexpectedly long ones, such as when ordered items were out of stock at the supplier, or when meetings were postponed.

Methods The changing conditions in the project made the product development process very important, at the same time as the project contained a high level of external uncertainties and evolving customer needs, the internal uncertainties were kept at a relatively low level by having a clear target from the outset. The internal uncertainties were also kept in check by the first phase being based on tested and verified standard components. This way it was possible to proceed as intended by just adapting the standardised system to the changes and still use it as a reference for improvements in the second phase. When the project reached the second phase, the system had matured to such a point that no major system changes needed to be performed. This meant that the NPD model was even more useful than in the first phase, as it could be followed step by step as a guide in how to proceed with the development work in the different sub-phases. The project group had also gained a great deal of insight through the first phase, which acted as a thorough pre-study when seen from the view of phase two, helping to clarify the problem and find external solutions in terms of standard enclosures.

The lean approach to product development has permeated the entire project work as the group early on realised the need to reduce the internal lead times and improve the quality of the result considering the delays and dependencies on external parties as well as the importance of the project to the company commissioning the project. This was done by initially focusing on defining customer values to reduce waste in the development process by not spending time and resources on features not useful to the customer. The flat organisation in the company in combination with a well-functioning decision structure within the

project group also helped reduce waste added by development processes. The project work was front-loaded in an as great extent as possible by working with sets of solutions concurrently and not just proceeding with a single idea after the concept generation. By doing so, having to go back and redo work when a feature or sub-system needed to be changed or eliminated could be avoided. Another important prerequisite of the project was to not try to revolutionise every subsystem and function, but rather focus on creating an optimal combination of standard solutions to maximise the performance of the product while mitigating risk by relying on tested and proven technologies. The importance of a project organisation based on cross-functional expertise is stressed in LPD, something that has been difficult to obtain as both project members have the same educational background. These difficulties have been overcome by close collaboration with suppliers, customers and external parties working on the other parts of the product to provide a wide knowledge basis to draw upon in the development to improve the project outcome.

Results One important aspect of the project was that the output from the first phase was a complete pre-serial enclosure, including the internal architecture concerning the PCB's, which could be tested and shown to customers to receive their feedback on its features. This evaluation was very important, as it provided a concrete benchmark for improvements; the product developed in the second phase should be better than the standard enclosure on a number of points identified in collaboration with experts and customers from the field.

The most important improvements that were made to the product compared to the standard enclosure were considered to be the implementation of a sealed connection compartment for both enclosures, as this was one of the main requirements from the outset of the project. Another highly appreciated change was the form factor of the product, as most customers claimed to have more space available in the vertical direction, meaning that it is better for the product to be high than wide or deep. The size constraint was mainly applied to the main unit, as the instrument unit provides more freedom regarding where to mount it. For the protection classes, only preparatory work have been done as they can only be evaluated once a product has been manufactured using the correct materials and processes. This work includes specifying a preliminary material, PA66, and a coating to improve EMC. Material selection must be a levelling between fulfillment of stated requirements (e.g. thermal properties, ATEX and CE) and the environmental impact. The environmental aspects should be considered whenever possible, which apart from the material selection might be when implementing a solution for handling of EMI, e.g. using mentioned material coating, so that this does not increase the negative environmental impact of the product more than necessary.

Based on the theory described on DFMA, it is easy to see the improvement to the product structure of the second phase compared to the standard enclosure as the number of parts that need assembly have been reduced by more than 30% for each enclosure. This should lead to savings in both assembly time and production cost, further reducing waste in the processes. The results from the estimated costs for tool manufacturing were not at all unreasonable. Investments in such equipment are deemed to be a major post of the production costs, which is why injection molding is normally used for high volume products. The market for industrial appliances as the one treated during this project is not considered target for a high volume production, but the gains in material properties applicable for the treated harsh environments and freedom of design outweigh the high cost. From the moldflow analyses it was found that both parts suffered from incomplete filling of the mold, which in both cases was due to the small material thickness in the sealing profile. As this was the main problem with both parts, the first step of a redesign would be to increase the material thickness.

It can be seen that the requirements stated in the requirement specification in the beginning of the project have all been covered, either by features in the product or by the preparatory work for protection class testing. The protection requirements are fulfilled by the design and materials selected. The requirements on the products physical dimensions, based on the size of the standard enclosure, has been fulfilled by the total volume of the product being less as well as the shape being better for mounting in installation cabinets. Interface requirements are fulfilled by the use of standard components and solutions, and the cost and assembly requirements are met by minimizing the number of components in the system.

As the project was considered live from the company's point of view, the standard enclosure in the first phase provided the possibility to test their technology, as they had no previous products. This also gave the project group the chance to take their ideas beyond just the concept stage, and into actual production and delivery of components, such as the keypad and the PCB fixtures in the first phase. The close collaboration with supporting actors such as component suppliers, construction consultants and industrial designers also had an important impact on the outcome of the project, as they provided knowledge and contacts allowing the product to reach a stage much closer to commercialisation than otherwise would have been possible.

The outcome of the project might have been different if the structure had been completely defined in an earlier stage, as the work on specific sub systems and components could have begun sooner. The way the project was carried out, however, meant that there could be a continuous dialogue between the group developing the enclosure and the external parties working on the internal components of the system. The results of this was a more balanced solution where both parties would compromise and try to find ways to heighten the performance of the product, rather than the project group creating an enclosure for the finished internals, which in turn had been developed without any concern for e.g. size.

6 Conclusion

As the project has evolved several iterations has taken the product to its present stage. In order to summarise the process and its compliance with the research questions that were posed at initiation of this project, conclusions has been made and they are presented in this section.

In answer to the first research question, it can be seen that the project resulted in a complete pre-series enclosure system based on standard components that can be used to test the technology and product architecture, as well as an alpha stage prototype of a system of customized enclosures adapted to the customer and company needs. The close collaboration with the suppliers and developers of the internal components meant changes due to their limitations could be implemented at an early stage. It also led to favorable internal and external product architectures, as the project group could act as mediators between them and the customers placing performance demands on the outside of the enclosure.

The outcome of the second phase of the project clearly answers the second and third research questions posed in the outset of this project by showing that it is possible to achieve a product that is aesthetically appealing at the same time as it gives off a robust and industrial feeling, something that has been stressed by customers as important for them to trust its reliability. Moving away from the traditional designs and standard enclosures also allow the company to profile themselves as an innovative company supplying cutting edge technology while keeping the core values of the industry. The early interaction with customers and stakeholders allowed the project group to find the requirements posed by the customers in terms of protection from the working environment and usability, the latter of which was also further aided by the use of DFE guidelines in the design work.

Dealing with delays and long lead times is a natural part of a development project, as external parties are not always available on demand. This highlights the importance of a good relationship in all ranks of the organization involved in development since involving e.g. manufacturers early mean that they are prepared when it is their turn to take on the product, reducing the time they need to react and start the production. Running processes in parallel when possible also means that the project is not affected as much if there are unexpected delays, as it is still possible to work on the other processes while waiting for the problems to be resolved.

The use of a LPD methodology such as early focus on customer values helped guide the project, even though the product architecture and conditions changed the requirements remained the same. It also helped when developing the concepts of phase two, as the concurrent engineering meant fewer loop backs and thereby a reduced development time. It is easy to see why the Lean methodology has had such great impact on the industry in later years, as the gains that can be made are substantial.

Recommendations for further development As the product nears commercialisation, there are some steps that should be taken in order to secure the quality of the end result. The next natural step would be the evaluation of the alpha prototype that has been created in the second phase of the project using the intended internal components to verify the architecture and assemblability. It would also be wise to investigate the reaction of customers and stake holders on the aesthetics and features when seen in real life and interacted with before pursuing the development further to assure that time and resources are not spent on developing something that is not received well by the market.

The first step in the further development that needs to be taken is to specify and verify the materials of the enclosure, as this affects the design of bosses and inserts as well as the

surface finish and durability in the different environments the product is intended to work in. The enclosure material also affects what steps need to be taken to ensure a sufficient EMC level, as well as the possibility of an ATEX classification, which is important e.g. if the company decides to move into the mining industry.

When the material is specified for all components, the preparations of the models can be started to adapt the design to the specific production processes, not just the general guidelines e.g. for injection molding that have been followed from the start. As tolerances have been assured, beta prototypes can be manufactured to test the protection classes and thermal performance at location of research partners to further ensure the viability of the product.

As the product is becoming ready for market, it might be worthwhile to investigate the potential of a product family, as there might be an interest for specific variants of the products, e.g. for application outside the initial specifications and in environments that are not possible with the materials decided for the first variant. This would encourage a further diversification of the technology's areas of application.

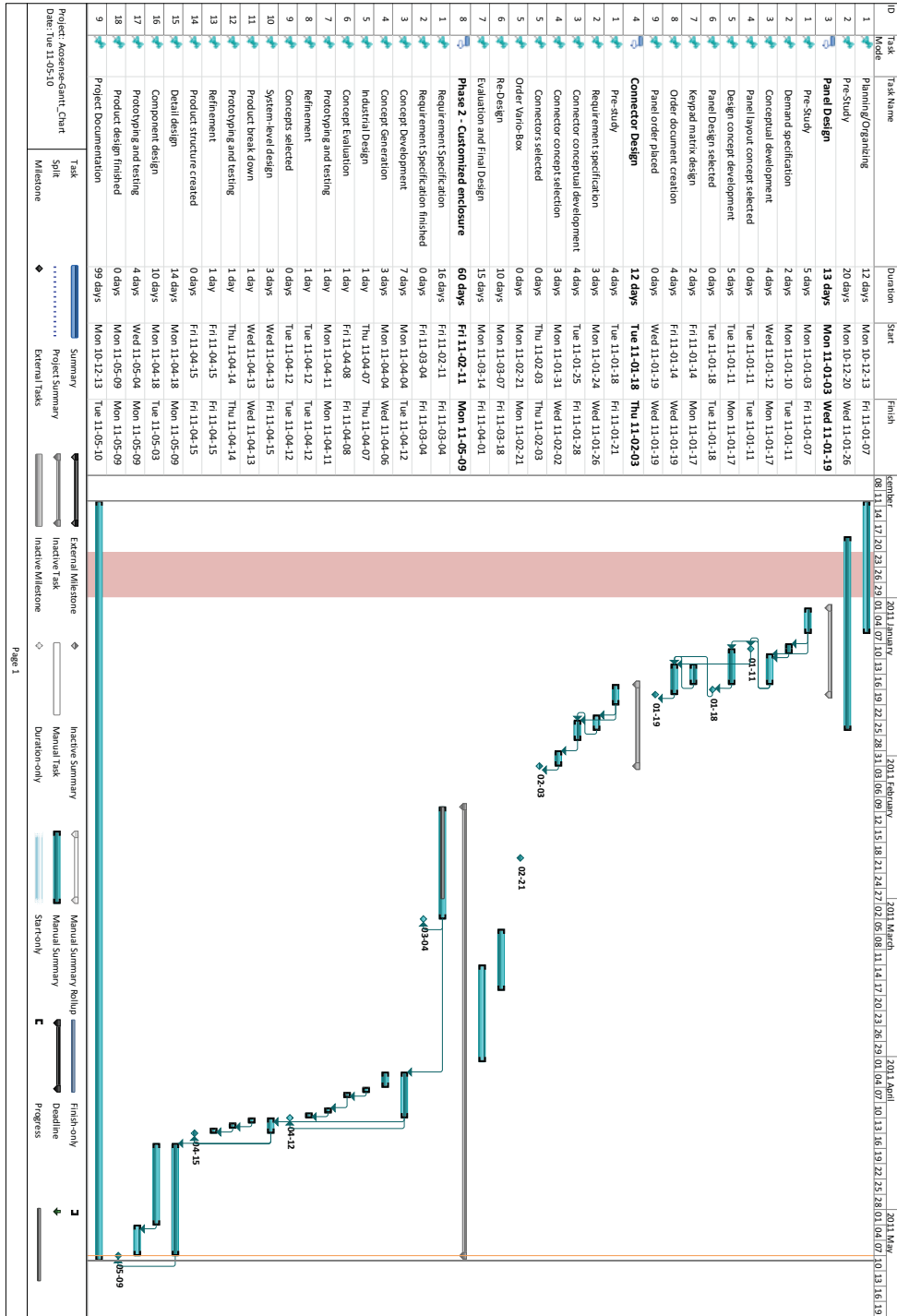
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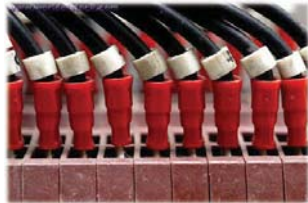
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Appendices

A Gantt Chart



B Moodboard



C Requirement Specification

CATEGORY	NEED	METRIC	UNIT	VALUE
1. Appearance	1. Aesthetically appealing	Aesthetically appealing	Subj.	>3
	2. Clearly recognizable product origin	Clearly recognizable product origin	Subj.	>4
	3. Robust feeling	Perceived feeling	Subj.	5
	4. Allow viewing of display	Viewing angle	°	120
2. Protection	1. Protected from water and dust	IP	Class	69
	2. Safe to use in explosive environments	ATEX	Category	1
	3. Withstand environment contaminants	Contaminant resistance	List	Black liquor, Colloidal silica...
	4. Withstand internal thermal loads	Therma range	°C	-30 -- 85
	5. Withstand external thermal loads	Therma range	°C	-30 -- 60
	6. A minimum of Electromagnetic Interference (EMI)	Electromagnetic Compatibility (EMC)	Binary	Non-emissive
	7. Possible to clean	Cleanability	Subj.	>4
	8. Withstand environmental breakdown	UV-resistance	Subj.	>3
	9. Non-flammable	Standards	UL94	V-0
3. Physical constraints	1. Requires a minimum of space	Volume	dm3	≤ 19*
	2. Separate compartment for PCB	No. of compartments	Value	2
	3. Adequate life length	Time in service	Years	>10
	4. Operable with gloves	Design for Usability	Subj.	>4
4. Interfaces	1. Mountable on existing structures	Existing structures	List	Cable Ladder (200, 400 & 600 mm), Wall
	2. Installable with standard tools	Standard tools for installation	List	Screwdriver, Wrench
	3. Mountable without PCB exposure	External fixtures	Binary	Yes
	4. Signals I/O	Connector types	List	List*
	5. PCB fixtures	Fixture	Type	Standard
	6. Monitor display	Existing display	Binary	Yes
	7. Keypad	Operating commands	List	Numerical input, Menu navigation...
5. Production	1. Is affordable	Cost/Unit	SEK	1500?
	2. Easy to assemble	Design for Assembly	Subj.	>4
	3. Easy to disassemble	Fasteners	Type	Screw
	4. Insensitive to variation	Expected non-defect products	%	99.99966 (Six Sigma)

*Main unit: Power, 2x Ethernet
 * Instrument Unit: Power, Ethernet, 2x Analog I, 1x Analog O, Calibration

(Subj. = Scale 1-5)

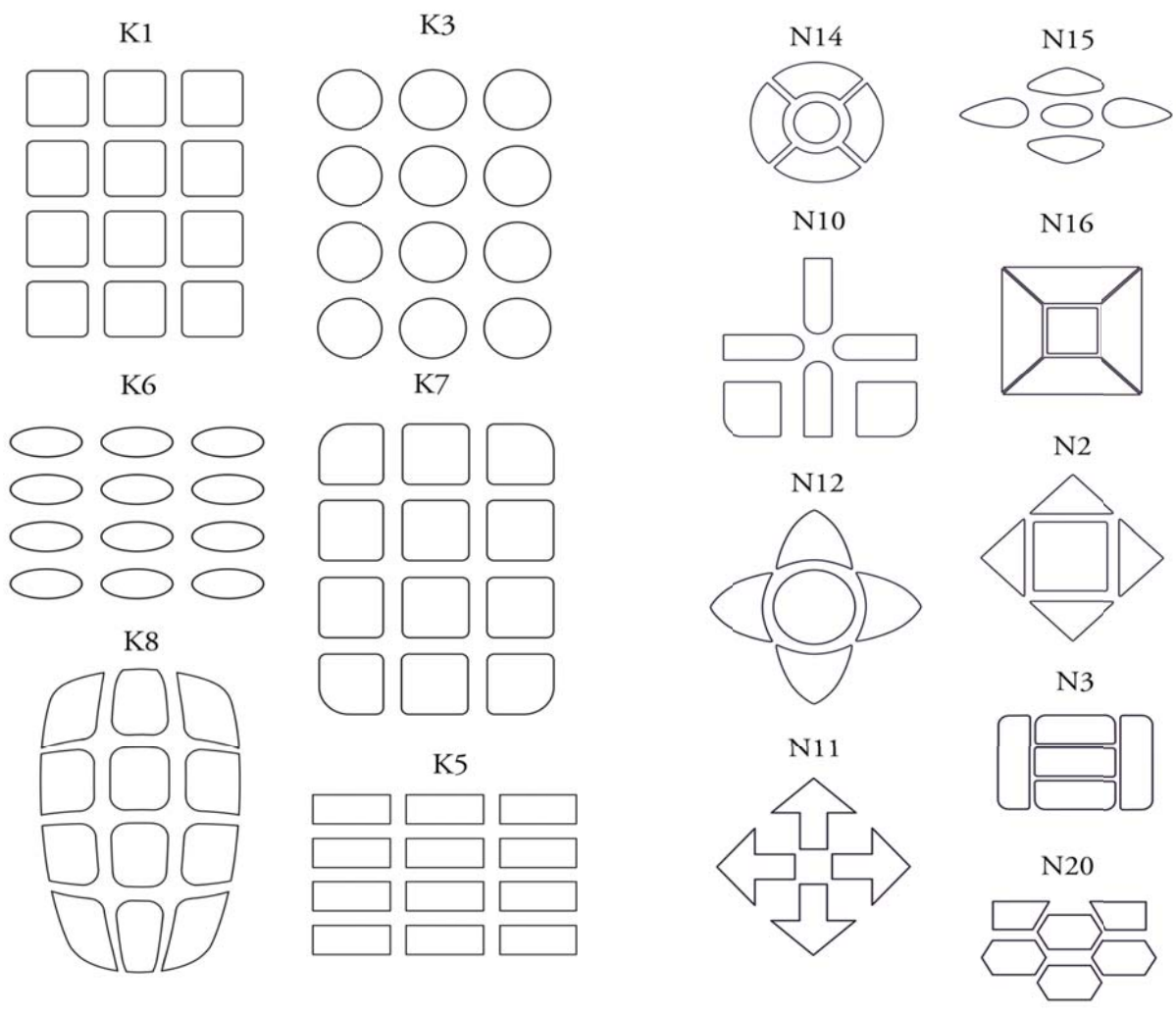
D Evaluation Matrices

		Concepts - Navigator Keys																			
Selection Criteria (Rating, 0-2)		N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	N11	N12	N13	N14	N15	N16	N17	N18	N19	N20
Confirm input	1	2	2	2	2	2	1	2	2	2	2	2	2	2	1	1	1	1	1	1	2
Navigate menus	2	2	2	2	2	2	2	0	2	2	2	2	2	2	2	2	2	2	2	2	2
Operable with gloves	1	1	1	1	1	1	1	1	1	1	2	2	2	1	1	2	1	1	1	1	2
Cleanable	1	1	1	1	1	1	1	2	1	1	2	1	1	2	1	1	1	1	1	1	1
Robust feeling	1	2	2	2	1	0	0	2	2	0	2	2	2	1	1	2	1	1	1	2	2
Fit into panel	2	1	1	2	2	1	1	2	2	2	2	2	2	1	2	2	1	2	1	1	1
Appealing design	1	1	2	0	0	0	1	0	1	1	2	2	2	0	1	2	2	1	2	2	2
Fullfill needs:	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sum:	9	10	11	9	7	7	7	10	9	13	14	12	9	No	9	11	9	9	10	11	12
Qualified (score ≥ 10)	No	Yes	Yes	Yes	No	No	No	Yes	No	Yes	Yes	Yes	No	No	Yes	Yes	No	No	Yes	Yes	Yes

		Concepts - Numerical Keys								
Selection Criteria (Rating, 0-2)		K1	K2	K3	K4	K5	K6	K7	K8	K9
Input values	2	2	2	2	2	2	2	2	2	2
Undo input	1	1	1	2	1	1	1	1	1	1
Operable with gloves	1	0	2	2	1	2	2	1	0	1
Cleanable	1	0	2	2	2	2	2	2	1	2
Robust feeling	2	1	1	1	2	2	1	2	1	2
Fit into panel	2	2	2	2	2	2	1	2	0	2
Appealing design	1	0	1	2	1	1	1	2	2	2
Fullfill needs:	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
Sum:	10	6	11	13	13	11	10	12	7	12
Qualified (score ≥ 10)	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes

Concepts	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14
	N1-K4	N18-K1	N17-K1	N15-K4	N12-K4	N11-K5	N12-K7	N3-K7	N2-K5	N18-K1	N15-K6	N19-K4	N20-K5	N20-K4

		Concepts - Keypads														
Selection Criteria (Rating, 0-3)		Weight (1-5)	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14
Cleanable	3	1	1	1	1	2	2	2	3	2	3	2	2	1	3	2
Robust feeling	4	1	2	2	2	1	2	2	3	2	3	2	1	1	2	2
Easy to use	5	2	1	1	2	2	2	3	3	2	1	1	1	2	3	3
Environmental friendly																
Fit into panel	2	2	1	2	2	1	2	1	2	2	3	1	1	2	2	2
Appealing design	5	3	1	2	2	1	3	3	2	2	2	1	1	2	2	2
Sum:	36	23	30	30	27	43	50	46	44	29	0	24	35	55	43	43
Ranking	6	12	8	10	10	5	2	3	4	9		11	7	1	5	5



Sub-system	Wall-E	Box-In-A-Box	Loosey	None	External
1. Compartment Setup	The Cap N	Windows '95	Slinky	Windows Vista	External
2. Panel Protection	O-ring	External protection	Sealing on hatch perimeter	Combo	
3. Sealing	Bird's nest	Captain Hook	The Hangman	Snappy	
4. Mounting					

Generated Concepts, Round 1:

	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6
B2-B3-B4-B5	C2-C3-C4-C5	D2-D3-C4-D5	E2-E3-B4-E5	B2-F3-D4-B5	C2-G3-B4-C5	

Round 1:

Criteria	Reference (Vario-box)	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6	Affected by subsystem
Manufacturability	0	0	0	-1	0	-1	0	0
Assembleability	0	0	1	-1	0	1	0	1
Usability	0	0	1	-1	-1	-1	1	1
Aesthetics	0	0	1	1	1	1	0	1
Installability	0	0	1	1	1	1	1	0
Robustness	0	0	0	1	-1	1	1	1
Cleanability	0	0	1	1	0	1	0	0
Sum:	0	0	5	1	0	2	2	4
Continue (Yes/No)	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Round 2:

Criteria	Reference (Concept 1)	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6	Affected by subsystem
Manufacturability	0	-1	-1	-1	0	-1	1-4
Assembleability	0	-1	-1	-1	1	0	1-4
Usability	0	-1	-1	-1	-1	0	2-3
Aesthetics	0	-1	-1	-1	0	0	1-3
Installability	0	1	1	1	1	0	1, 4
Robustness	0	1	-1	-1	1	0	2-3
Cleanability	0	1	-1	-1	1	1	2-3
Sum:	0	-1	-5	2	1	-3	
Continue (Yes/No)	Yes	No	No	Yes	Yes	No	

Further Evaluation and Improvement

Concept 1	Name
B2-B3-B4-D5	Cubic
E2-F3-B4-E5	ModBox
B2-F3-B4-B5	KIWI

Compartment setup

Wall-E

Box-in-a-box

Loosey

None

Seals

O-ring

External protection

Sealing on hatch perimeter

Panel protection

The Cap'n

Windows 95

Slinky

Windows Vista

Combo

External

Mounting solution

Bird's nest

Captain Hook

The Hangman

Snappy

Criteria

Manufacturability

Assembleability

Usability

Aesthetics

Installability

Robustness

Cleanability

Fixed separator, separate compartment. Above, under or on the side. I.e. Vario-Box.

Electronics compartment mounted on the inside of the panel. Outer compartment for cables and connectors.

Removable separator only accessible from electronics compartment.

External connectors that eliminates the need for separate compartments.

Sealing profile pressed between cover and base

External cover mounted on the enclosure

Sealing profile around the outside of the split line

Hatch with integrated protective visor.

Transparent ordinary hatch. I.e. Vario-Box.

Sliding hatch either from side, top or under.

Opaque ordinary hatch. I.e. Vario-Box.

Integrated visor in box design and a transparent hatch.

Ordinary hatch with external visor.

Mounting integrated in box design.

Hooks on the back of the box mounted on existing structure.

Plate with hook-and-hole interface.

Pre-mounted frame with snap locks.

Assesses the complexity of the manufacturing process. This criteria is also to some extent related to production cost.

Assesses the complexity of the assembly process. Based e.g. on number of moments and parts in assembly sequence as well as accessibility for assembly.

Based on the intuitiveness and ability to view and interact with the equipment.

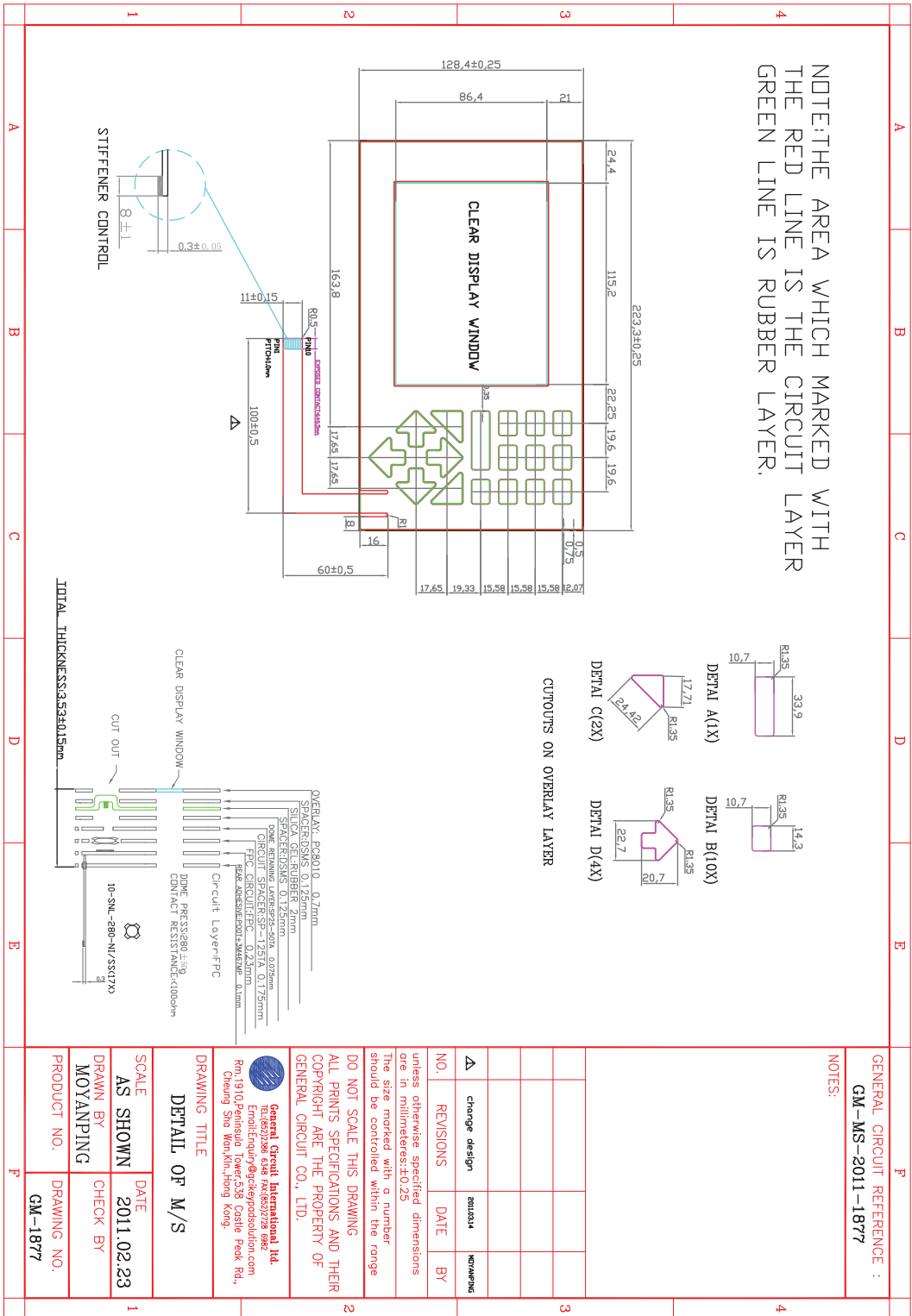
Assessment of the possibility to communicate product origin and the aesthetically appearance in the product's design.

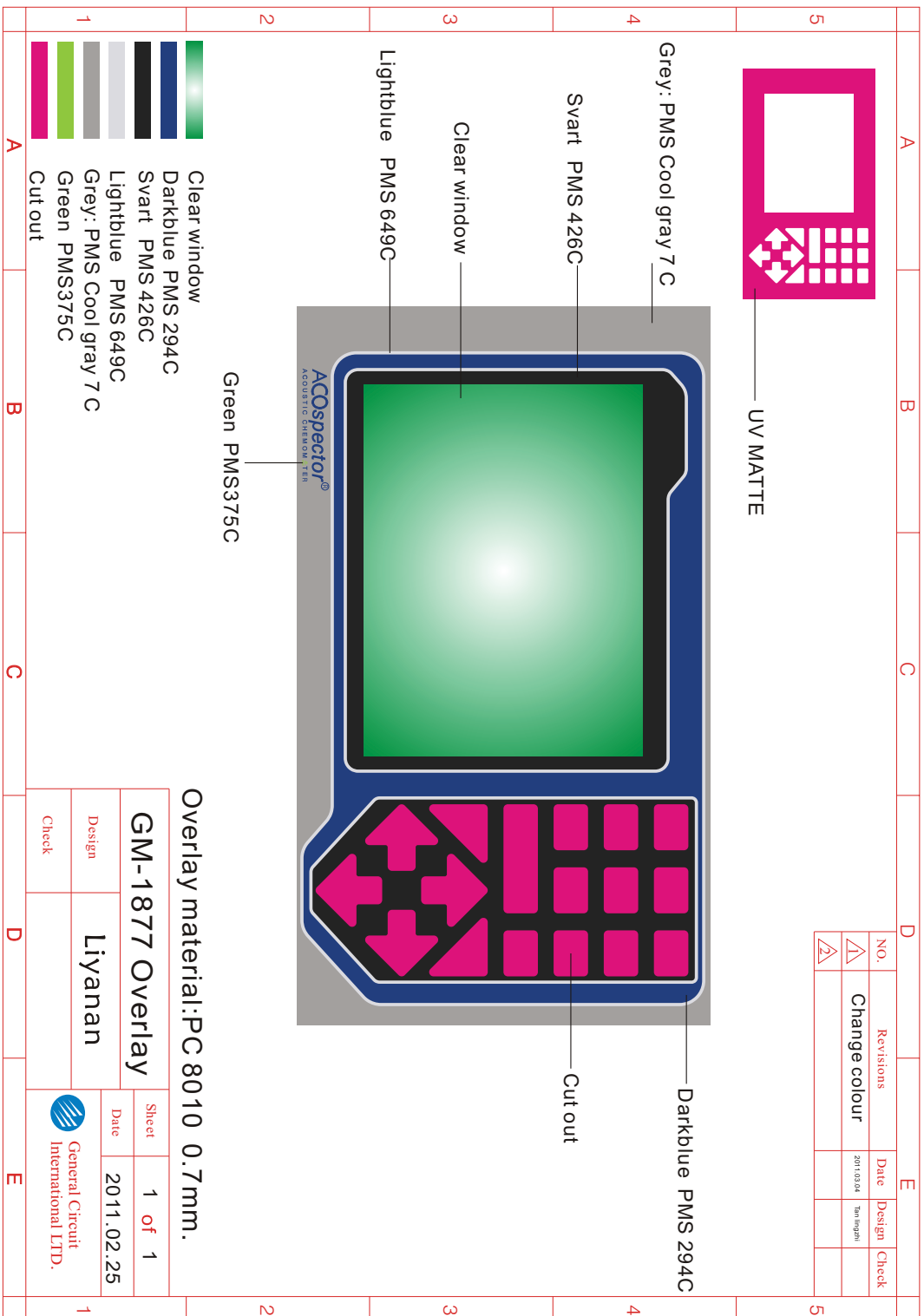
Evaluates the complexity and compatibility in mounting on existing structures such as cable ladders and walls without internal exposure.

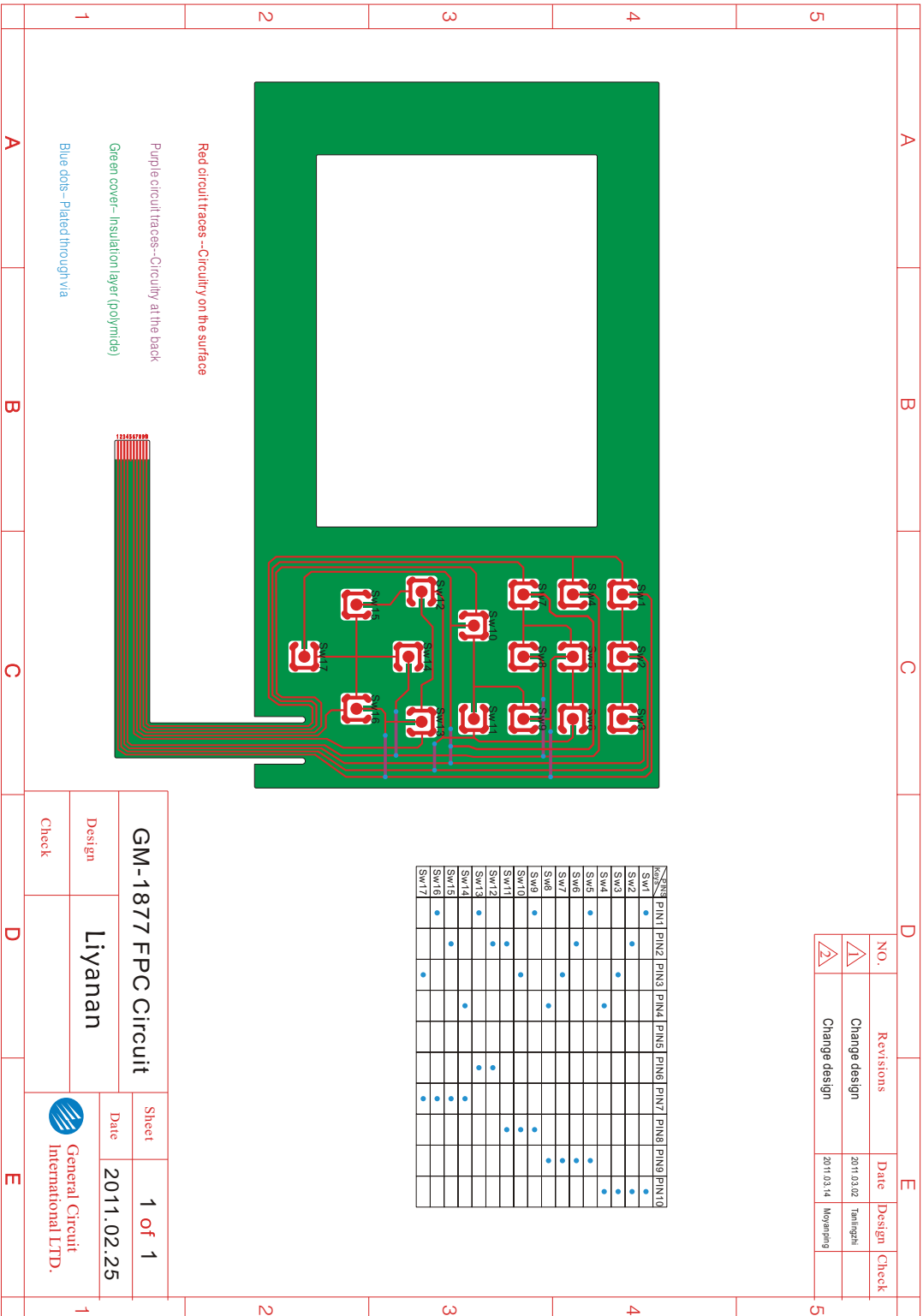
Evaluates the products ability to withstand harsh environments and physical abuse.

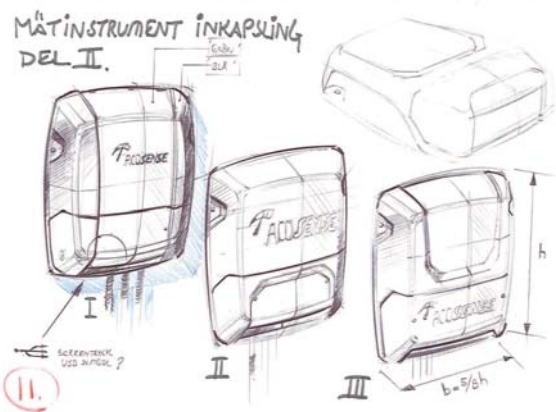
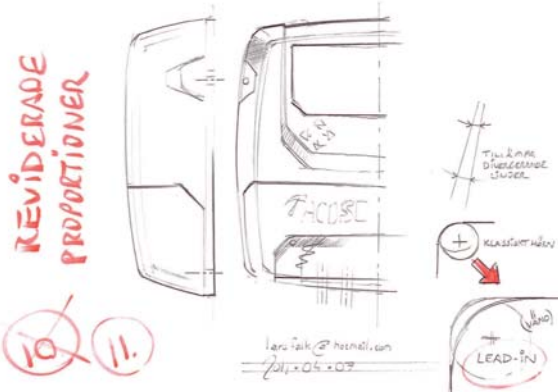
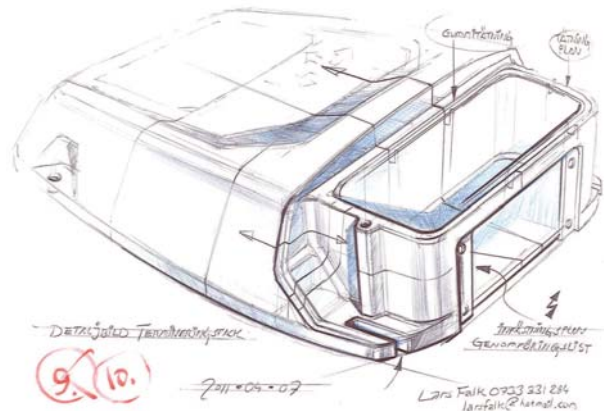
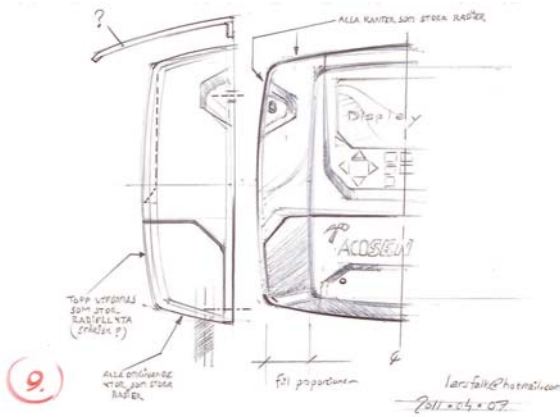
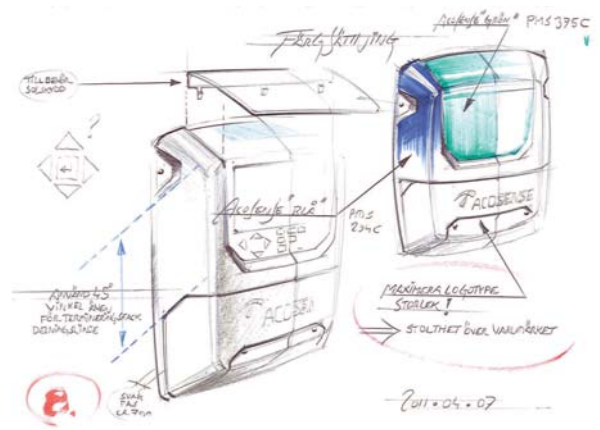
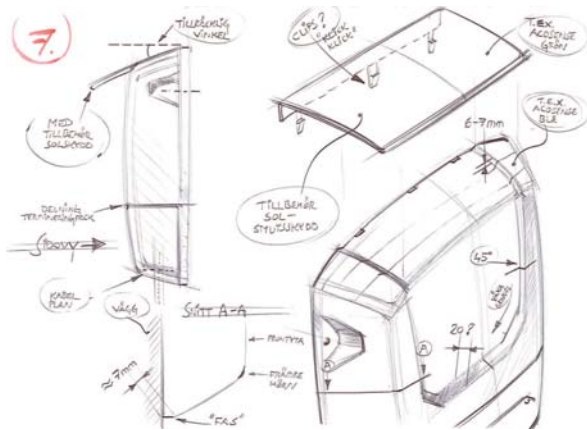
Assesses the amount of maintenance needed as well as the possibility to clean based on factors like inaccessible corners and dirt traps.

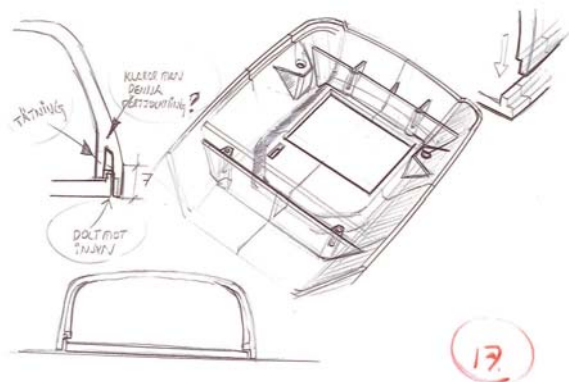
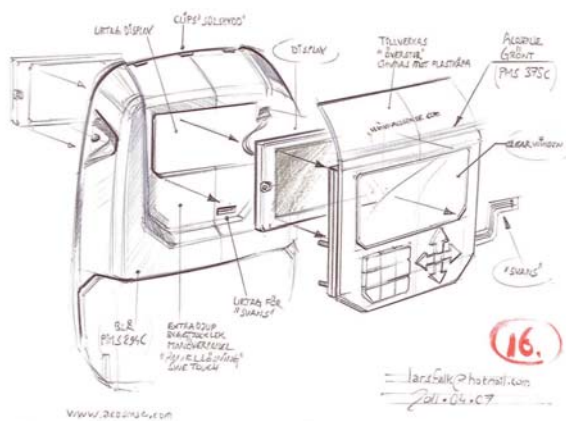
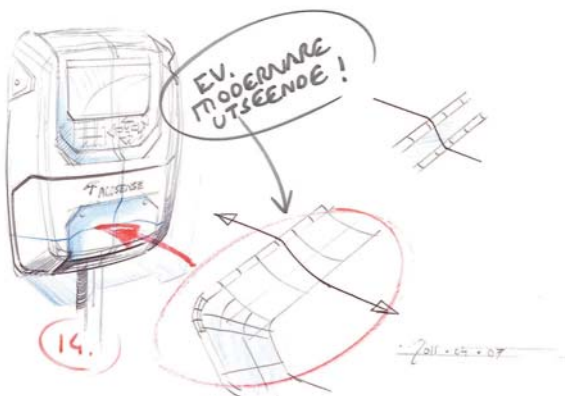
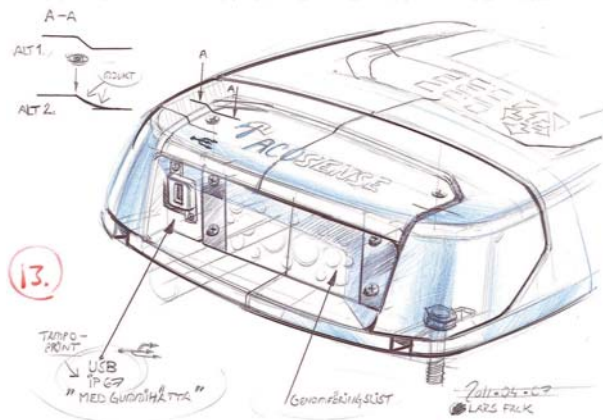
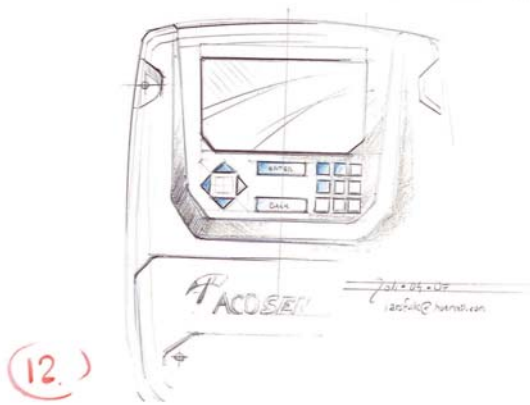
E Order Documentation for Phase One

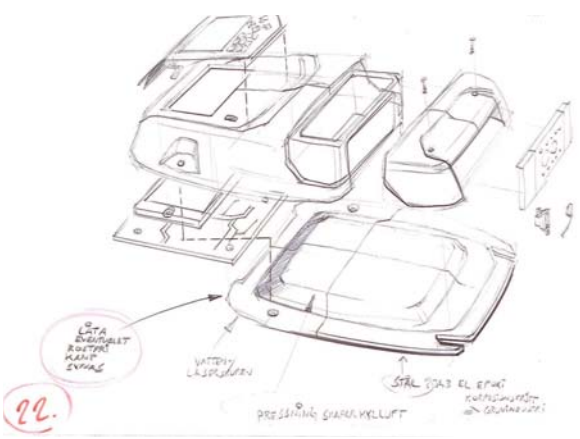
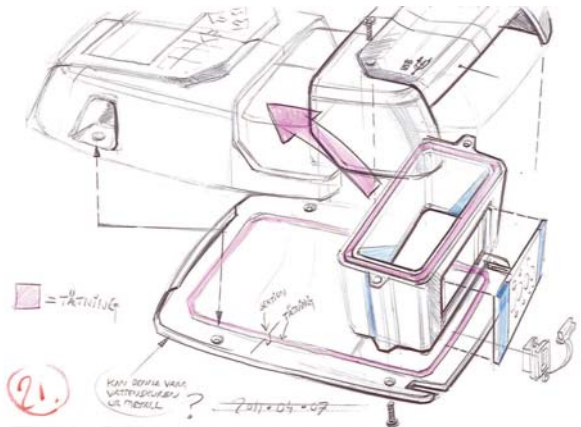
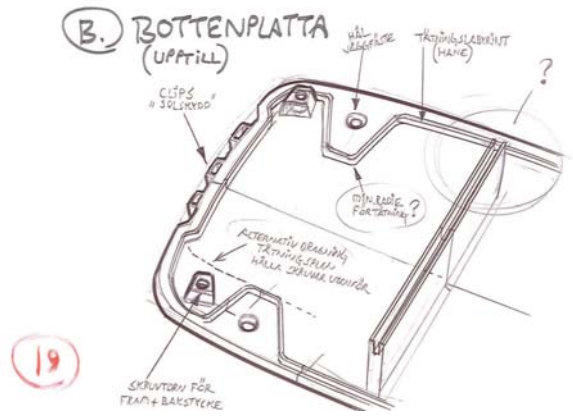
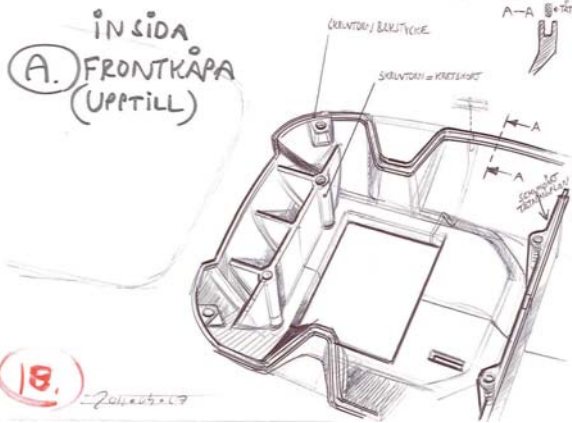


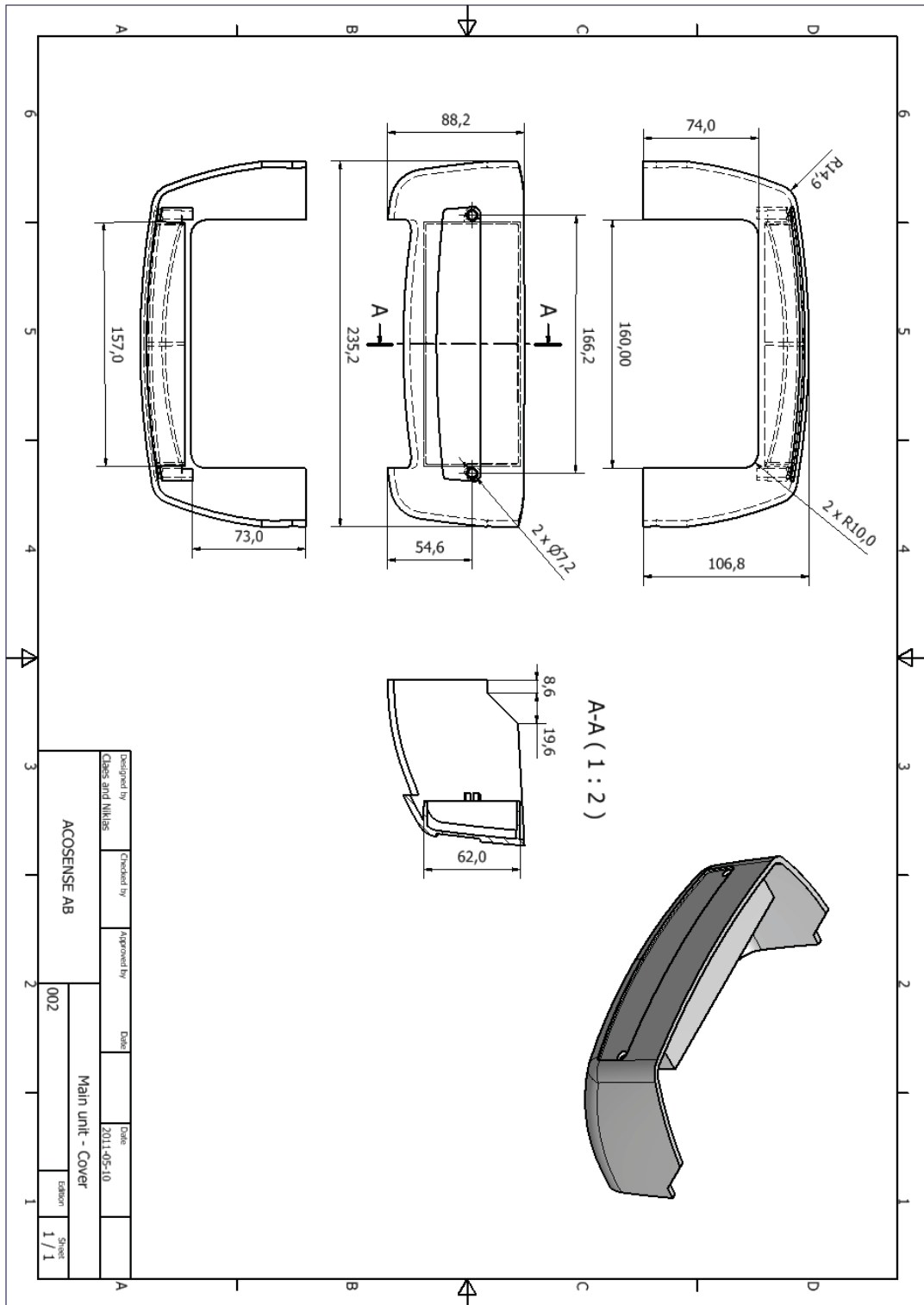


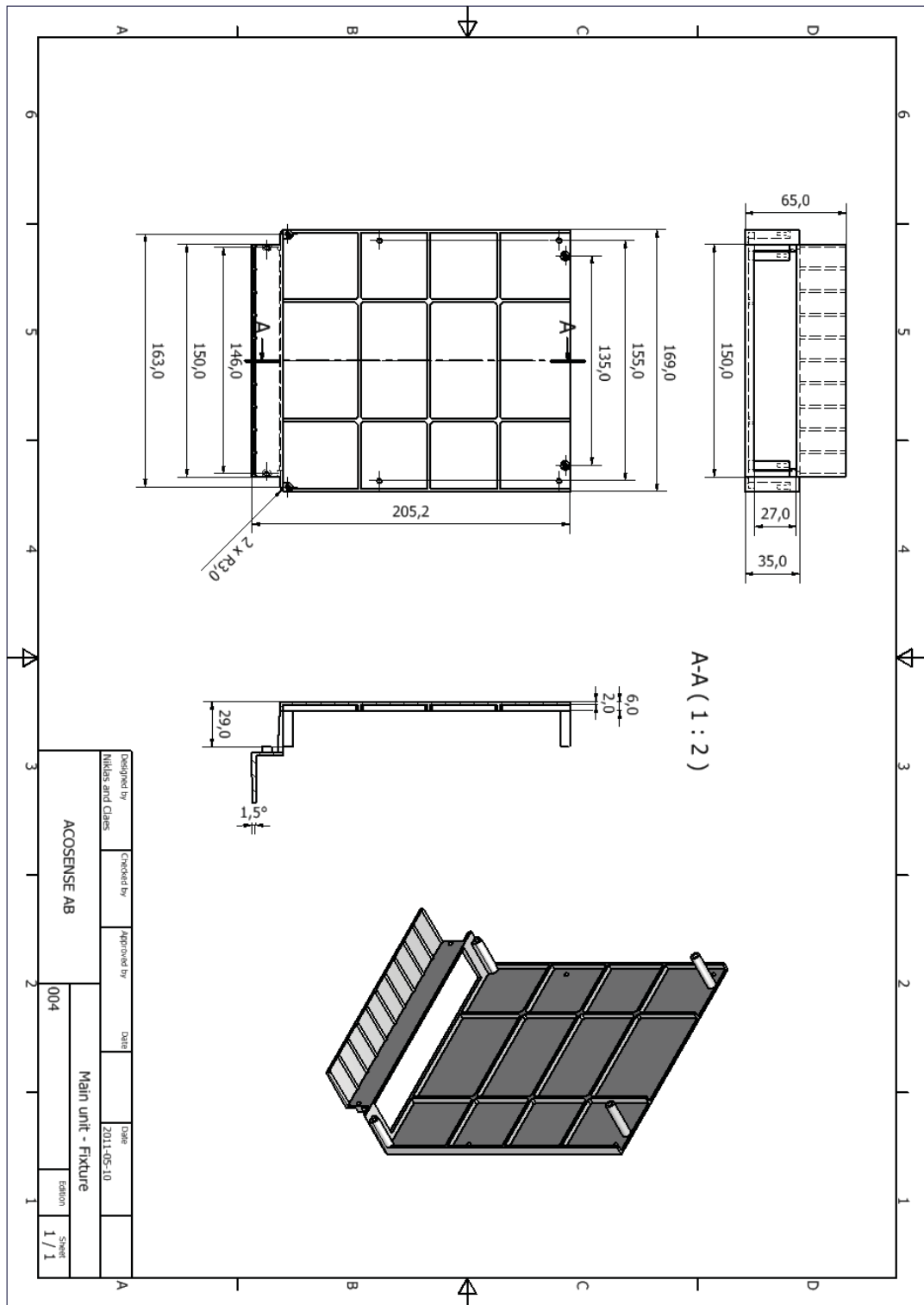


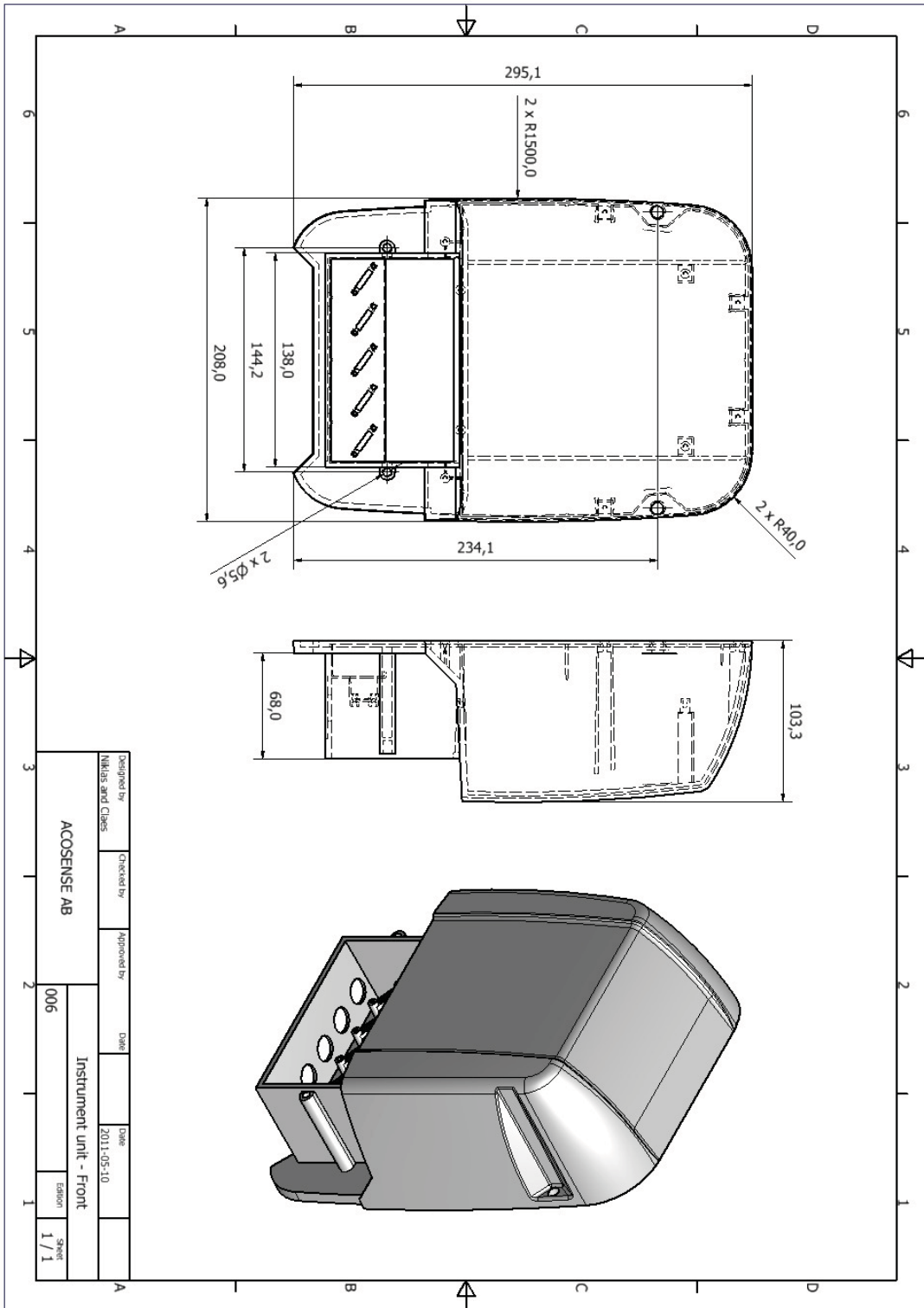


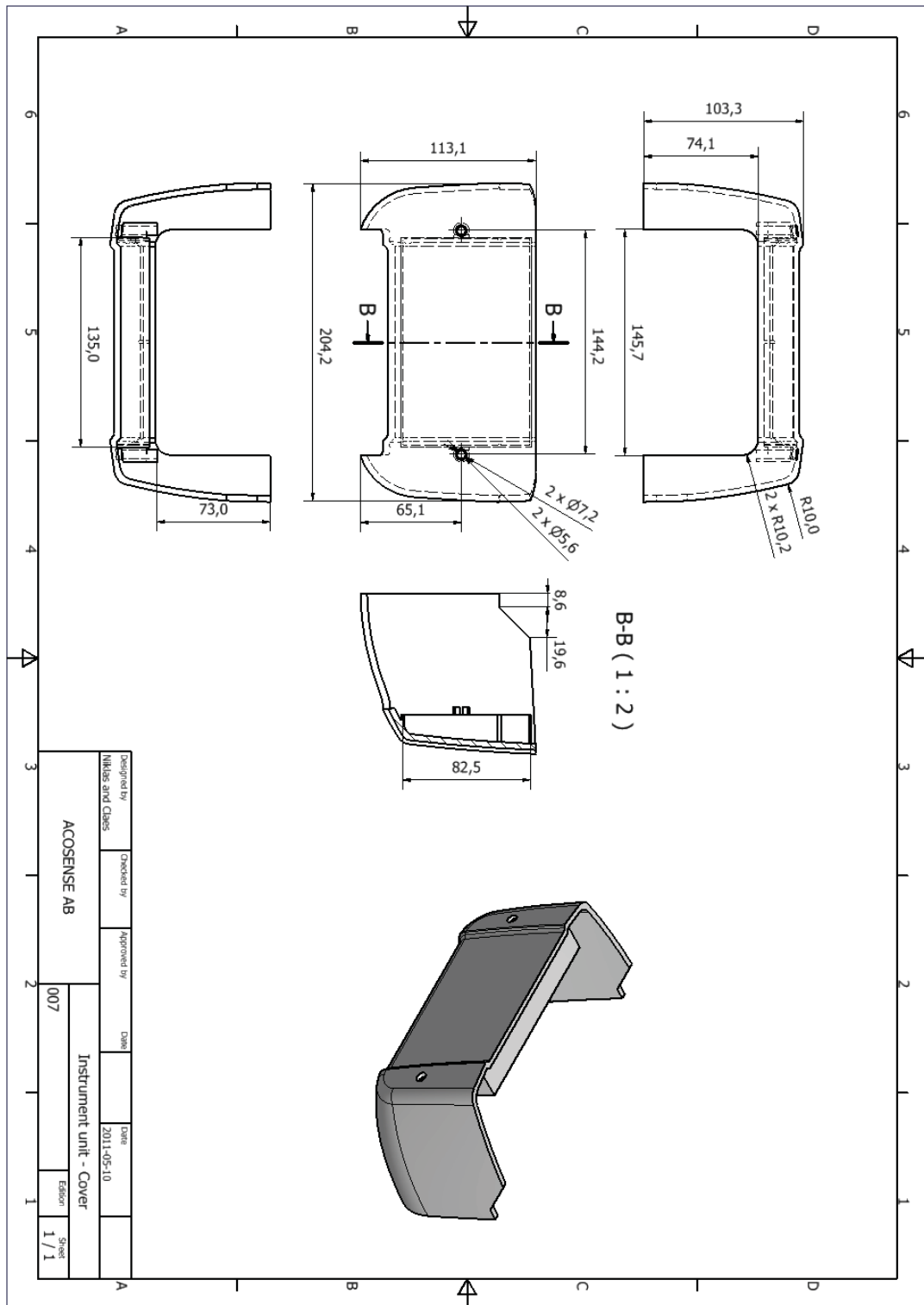


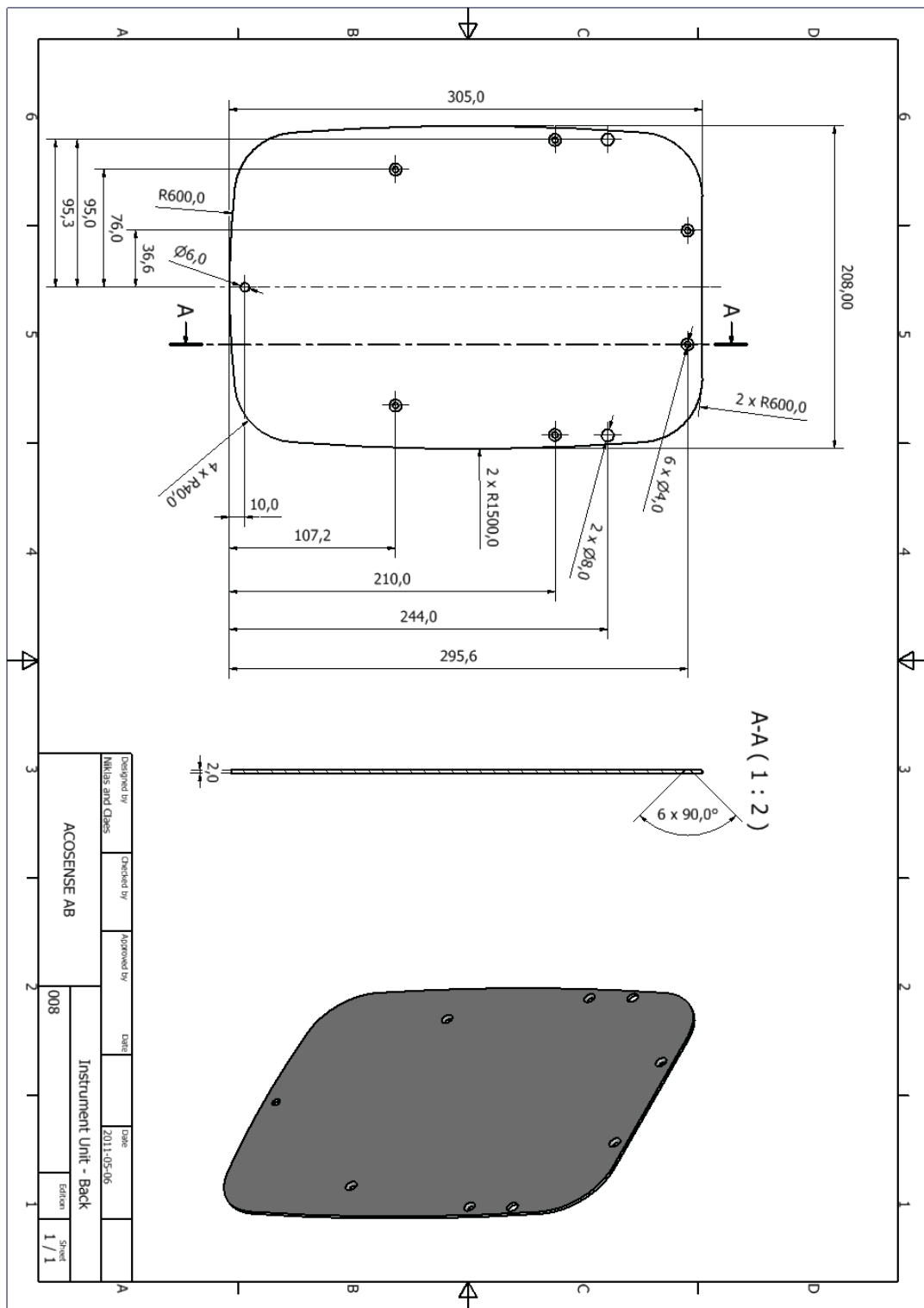


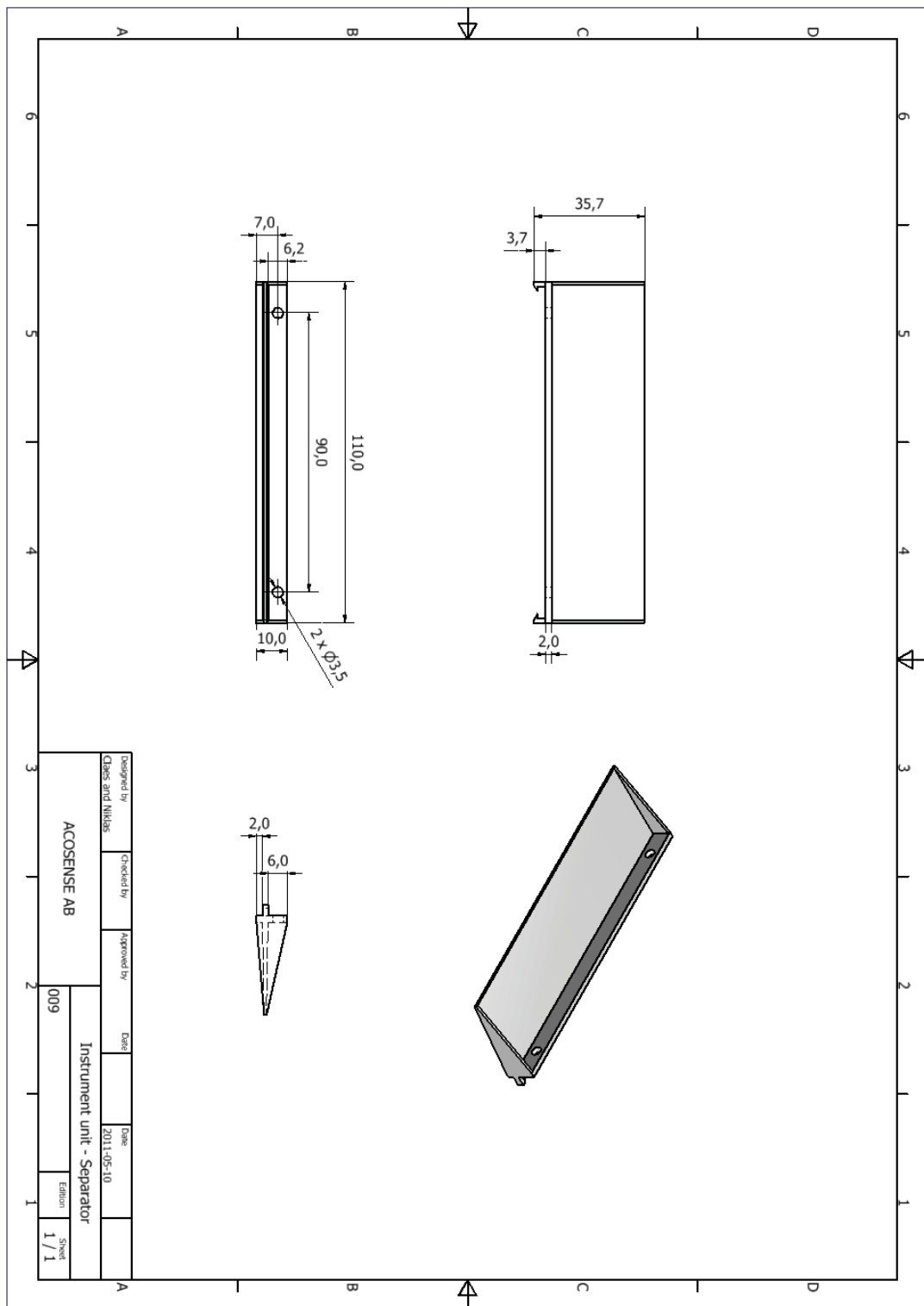


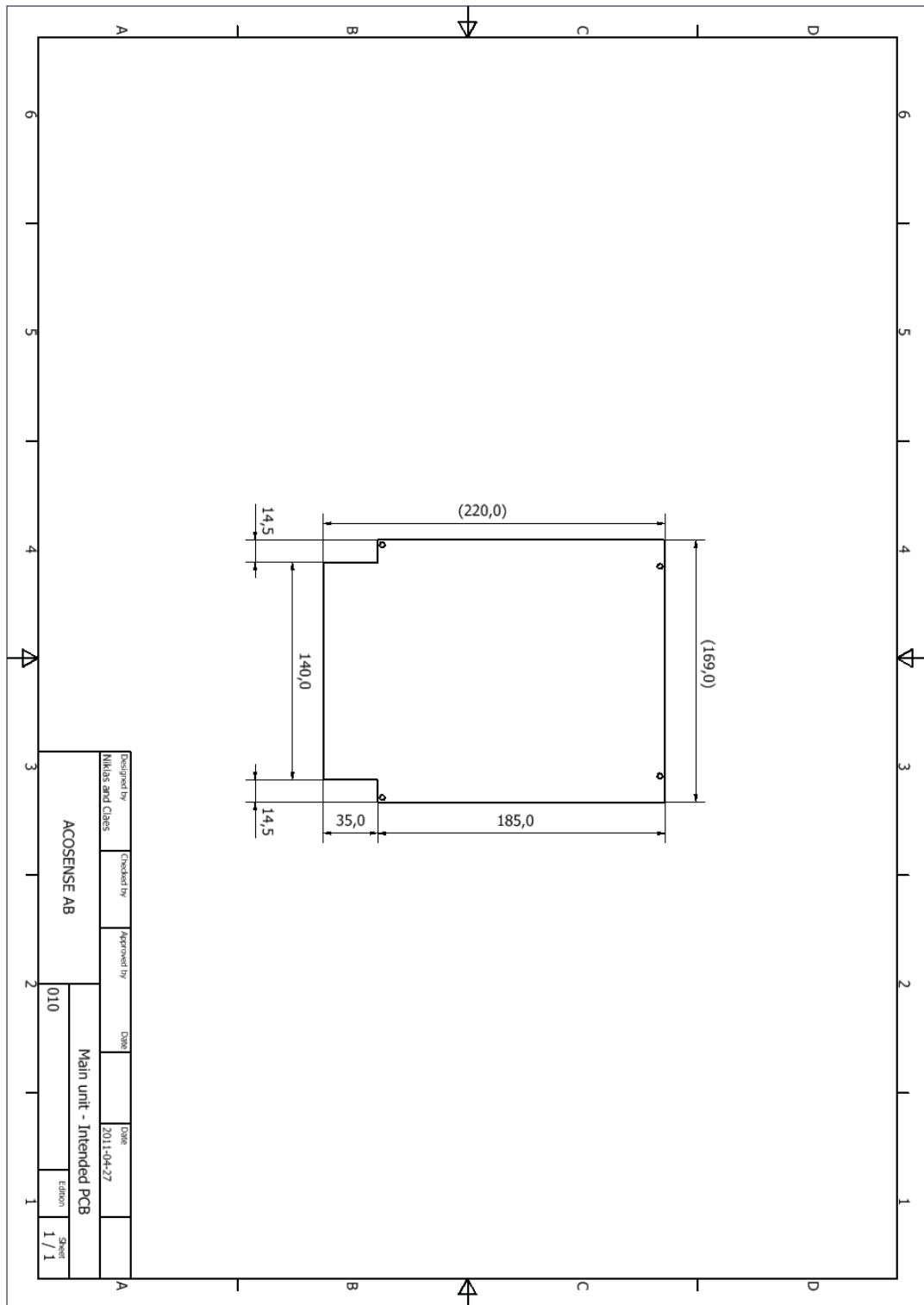


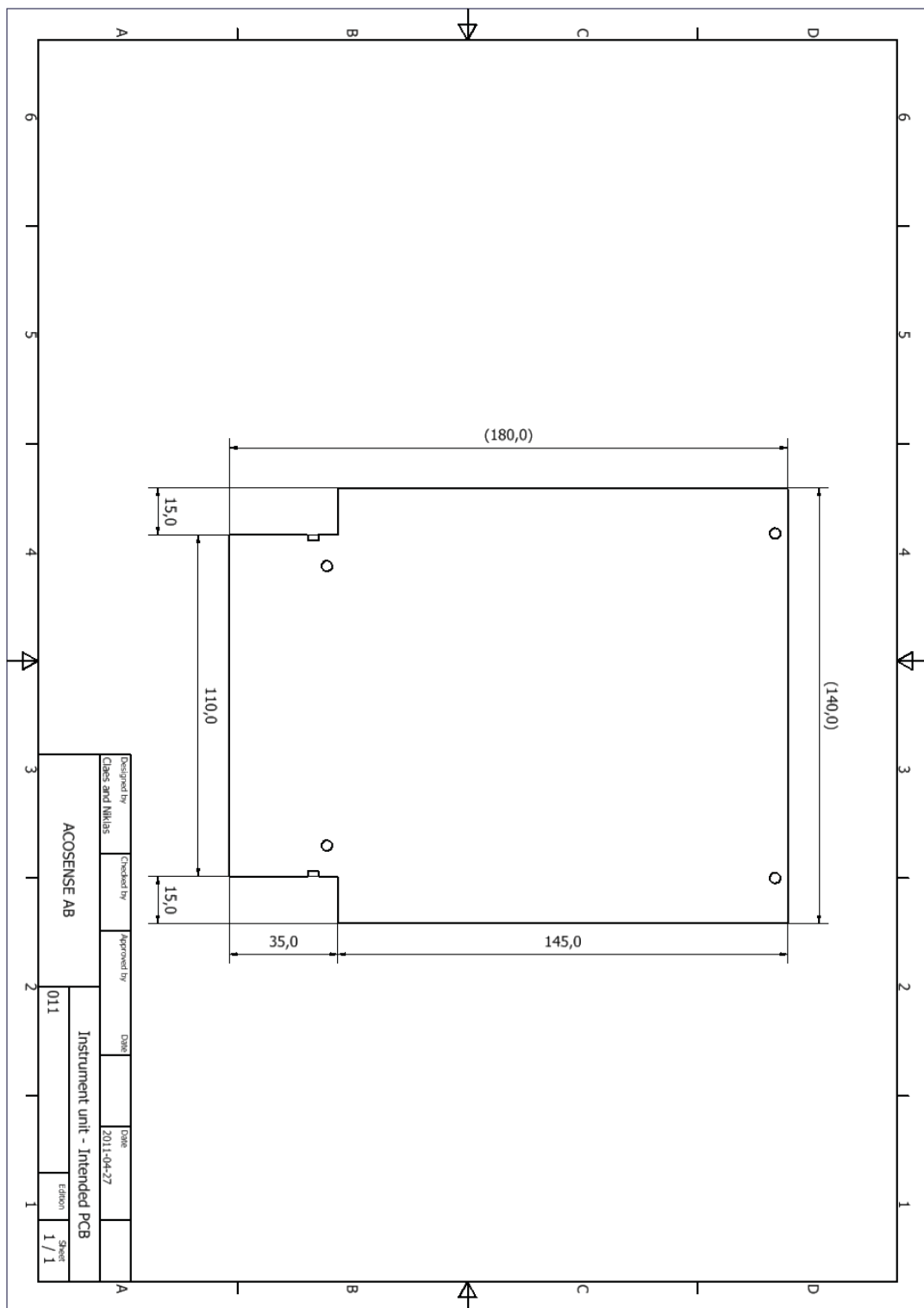












H Tool Manufacturing Cost Estimation

```
clc
close all
clear all

%% Mold Manufacturing Cost Estimation

Re = 6.09; %exchange rate USD —> SEK

%Main unit – Front, Cover, Fixture, Compartment cover
%Instrument unit – Front, Cover, Separator wall

N_mu = 4; %number of components
N_iu = 3;

%area of mold base cavity for components, cm2
Ac_mu = [(32.9+15)*(24.4+15) (23.5*8.7)
          (16.9*(20.5+7.5)) (3.9*5.6)];
Ac_iu = [(30.5+15)*(20.8+15)
          (20.4*8.9) (3.6*11)];

%combined thickness of cavity and core plates in mold base, cm
hp_mu = [(11.0*2) (10.7*2) (6.5*2) 2*2];
hp_iu = [(10.5*2) (10.3*2) 1*2];

for i=1:N_mu;
Cb_mu(i) = Re*(1000+0.45*Ac_mu(i)*hp_mu(i)^0.4);
end
    for j=1:N_iu
        Cb_iu(j) = Re*(1000+0.45*Ac_iu(j)*hp_iu(j)^0.4);
    end

%projected part area, cm2
Ap_mu = [(32.9*24.4) (23.5*8.7) (16.9*20.5) (3.9*5.6)];
Ap_iu = [(30.5)*(20.8) (20.4*8.9) (3.6*11)];

%additional number of manufacturing hours for ejection system
for i=1:N_mu;
Me_mu(i) = 2.5*sqrt(Ap_mu(i));
end
    for j=N_iu
        Me_iu(j) = 2.5*sqrt(Ap_iu(j));
    end

%estimated inner complexity
Xi_mu = [5.5 2.5 2 0.2];
Xi_iu = [5.5 2.5 1.5];

%estimated outer complexity
```

```

Xo_mu = [3 2 2 0.2];
Xo_iu = [3 2 1];

%additional number of manufacturing hours associated
%with geometrical features
for i=1:N_mu;
Mx_mu(i) = 5.83*((Xi_mu(i)+Xo_mu(i))^1.27);
end
    for j=1:N_iu
        Mx_iu(j) = 5.83*((Xi_iu(j)+Xo_iu(j))^1.27);
    end

%number of manufacturing hours for one cavity and core
%with low geometrical complexity
for i=1:N_mu;
Mpo_mu(i) = 5+0.085*Ap_mu(i)^1.2;
end
    for j=1:N_iu
        Mpo_iu(j) = 5+0.085*Ap_iu(j)^1.2;
    end

%number of side-pulls
sp_mu = [4 0 1 0];
sp_iu = [4 0 1];

%number of internal lifters
il_mu = [0 0 0 0];
il_iu = [0 0 0 0];

%number of unscrewing devices
us_mu = [0 0 0 0];
us_iu = [0 0 0 0];

%surface finish according to tabulated percentage values
sf_mu = 0.15;
sf_iu = sf_mu;

%percentage increase for tolerances
tol_mu = [0.2 0.2 0.05 0.05];
tol_iu = [0.2 0.2 0.05];

%5 percent added if textured surface required
t_mu = [0 0 0 0];
t_iu = [0 0 0];

%parting plane factor
fp_mu = [1.25 1.25 2 0];
fp_iu = [1.25 1.25 1.25];

for i=1:N_mu

```

```

Ms_mu(i) = fp_mu(i)*sqrt(Ap_mu(i));
end
    for j=1:N_iu
        Ms_iu(j) = fp_iu(j)*sqrt(Ap_iu(j));
    end

%total point score
for i=1:N_mu
M_mu(i) = (Me_mu(i) + Mpo_mu(i))+Mx_mu(i)+sp_mu(i)*65+
            il_mu(i)*150+us_mu(i)*250+sf_mu*(Me_mu(i)+
            Mpo_mu(i)+Mx_mu(i))+tol_mu(i)*Mx_mu(i)+
            0.05*t_mu(i)*(Me_mu(i) + Mpo_mu(i)+Mx_mu(i))+Ms_mu(i);
end
    for j=1:N_iu
        M_iu(j)=(Me_iu(j)+Mpo_iu(j))+Mx_iu(j)+sp_iu(j)*65+
            il_iu(j)*150+us_iu(j)*250+sf_iu*(Me_iu(j)+
            Mpo_iu(j)+Mx_iu(j))+tol_iu(j)*Mx_iu(j)+
            0.05*t_iu(j)*(Me_iu(j) + Mpo_iu(j)+Mx_iu(j))+
            Ms_iu(j);
    end
end

%assumed average hourly rate for tool manufacturing
hr = 300;

for i=1:N_mu
M_mu(i) = (M_mu(i)*hr)+Cb_mu(i);
end
    for j=1:N_iu
        M_iu(j) = (M_iu(j)*hr)+Cb_iu(j)
    end
end

```