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Product development of a gripping mechanism for a flexible 3D stretch bending machine for industrial applications

Exploring the concepts of set-based
concurrent engineering

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Summary

English

High strength aluminum components are increasingly popular in the automotive industry. Development of novel manufacturing machines for these components is required to gain a competitive edge. An automotive parts manufacturer has previously constructed a flexible three-dimensional stretch bending machine for aluminum extrusions. The manufacturer is going to develop a new machine of similar design, but with a new gripping mechanism.

Set-based concurrent engineering (SBCE) is a design methodology which regards ”sets” of design possibilities for each sub-system of the product. ”Sets” refer simply to areas in the design space. This area is gradually narrowed through-out the development process by considering all aspects of the engineering effort concurrently. The sets converge slowly towards an intersection of each sub-system sets. This is intended to increase flexibility to optimise the system. SBCE is fairly new to western societies and requires more industrial case studies to gain credibility.

This paper presents a case study of SBCE at an automotive parts manufacturer regarding product development of a novel gripping mechanism for a new flexible three-dimensional stretch bending machine. The researcher was co-located with the automotive parts manufacturer over a duration of four months to observe and interview selected employees.

A literature study of SBCE was conducted which identified principles, activities and a process model for the product development. Additionally, research gaps were identified.

The product development process was structured and conducted according to the findings of the literature study. Broadly speaking, this involved identifying the project’s value for the customer to correctly position the product development, identifying the feasible region wherein 845 different system concepts were generated and gradually narrowed to a single, final concept. The novel gripping mechanism was evaluated through CAE and performs within the requirements. Detailed design specifications are presented in the paper.

Based on experience from the case study, SBCE is discussed and observations and suggestions regarding the research gaps are presented. Design considerations for the continued development of the novel gripping mechanism are presented.

Norwegian

Aluminiumskomponenter av høy styrke har økende populæritet i bilindustrien. Utvikling av nye produksjonsmaskiner for disse komponentene er nødvendig for å tilegne seg konkurransedyktighet. En bildelprodusent har tidligere konstruert en fleksibel, tredimensjonal strekkbøyingsmaskin for aluminiumsekstruderinger. Produsenten skal utvikle en ny maskin av lignende design, men med en ny gripemekaisme.

Set-based concurrent engineering (SBCE) er en produktutviklingsmetode som angår "sett" av designmuligheter for hvert delsystem av produktet. "Sett" refererer til areal i designområdet. Dette arealet er gradvis snevret gjennom utviklingsprosessen ved å ta i betraktning hele ingeniørvirksomheten parallelt. Dette er ment å øke fleksibilitet til å optimalisere systemet. SBCE er rimelig nytt i det vestlig samfunn og behøver fler industrielle kasusstudier for økt troverdighet.

Denne oppgaven presenterer et kasusstudie av SBCE ved en bildelprodusent angående produktutviklig av en ny gripemekanisme for en ny fleksibel, tredimensjonal strekkbøyingsmaskin. Forskeren var samlokalisert med bildelprodusenten over en periode på fire måneder for observere og intervjue utvalgte ansatte.

Med dette som mål ble et litteraturstudie av SBCE utført, som identifiserte prinsippene, aktivitetene og prosessmodellen for produktutvklingen. I tillegg ble forskningshull identifisert.

Produktutviklingsprosessen ble strukturert og utført i henhold til funnene i litteraturstudiet. Grovt sett involvererte dette å identifisere prosjektets verdi for kunden for å posisjonere produktutviklingen korrekt, å identifisere gjennomførbare regioner hvori 845 forskjellige systemsett ble generert og gradvis snevret til et enkelt, endelig konsept.

Den nye gripemekanismen ble evaluert ved hjelp av dataassistert konstruksjon og presterer innenfor kravene. Detaljerte designspesifikasjoner er presentert i oppgaven.

Basert på erfaring fra kasusstudiet er SBCE diskutert og observasjoner og forslag angående forskingshullene er presentert. Designbetraktninger for å videreutvikle den nye gripemekanismen er presentert.

Preface

This thesis has been submitted to the Norwegian University of Science and Technology (NTNU) for the degree of Master of Science (M.Sc.). The work has been carried out at the Department of Mechanical and Industrial Engineering (MTP) under the supervision of Torgeir Welo and Geir Ringen. The work was conducted in the period of April-September 2018. The work counted for 30 ECTS.

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Abbreviations

3DBM 2500-A	=	The flexible, three-dimensional stretch bending machine as constructed
3DBM	=	The flexible, three-dimensional stretch bending machine to be constructed
SBCE	=	Set-Based Concurrent Engineering
PD	=	Product development
CAE	=	Computer aided engineering
ToC(s)	=	Trade-off curve(s)
SBD	=	Set-based design
PBD	=	Point-based design
LPD	=	Lean product development
CE	=	Concurrent Engineering
SE	=	Sequential Engineering
LeanPPD	=	Lean Product and Process development
CAD	=	Computer aided design
PSD	=	Preference Set-Based Design
ISBD	=	Instant Set-Based Design
2DBM	=	The two-dimensional stretch bending machine
FEM	=	Finite element method

Chapter 1

Introduction

1.1 Background

The automotive industry aims to reduce the weight of automotive components in order to increase fuel efficiency. High strength aluminum components have proven to be a good substitution of traditional steel components in this regard, most notably for component groups highlighted in Fig. 1.1.

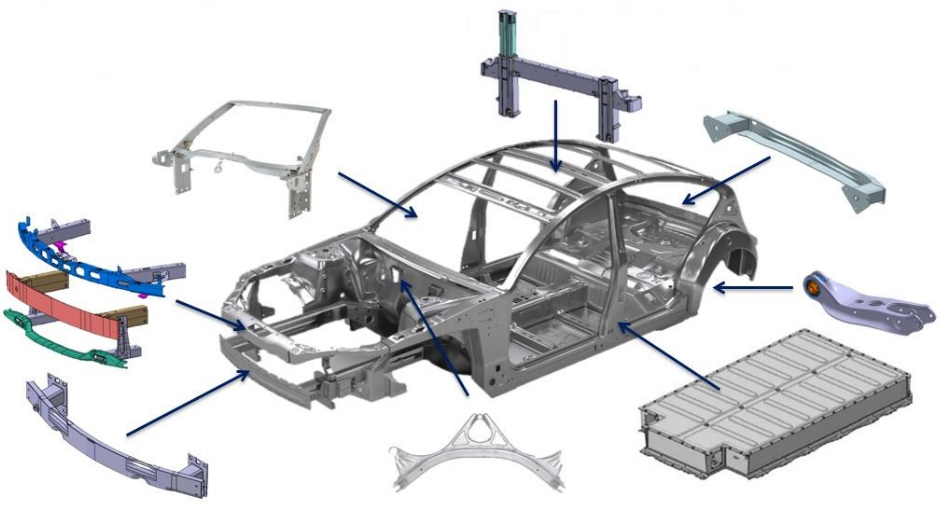

Figure 1.1: Automotive components of extruded aluminum (Benteler Automotive, 2018).

Low weight-to-strength ratio, recyclability, formability, and corrosion resistibility are among the main factors for high strength aluminum's applicability (Welo & Paulsen, 2001). Still, there are certain factors hindering further advancement, most notably a base material price more than four times higher than traditional steel (MetalMiner, 2018) and competence regarding aluminum products and productions processes (Welo & Paulsen, 2001).

An automotive parts manufacturer has developed a flexible, three-dimensional stretch bending machine – termed ”3DBM 2500-A” – for aluminum extrusions, as depicted in Fig. 1.2. The ”3DBM 2500-A” provides flexibility and repeatability. The automotive parts manufacturer is to develop a machine of similar design – in this paper termed ”3DBM”.

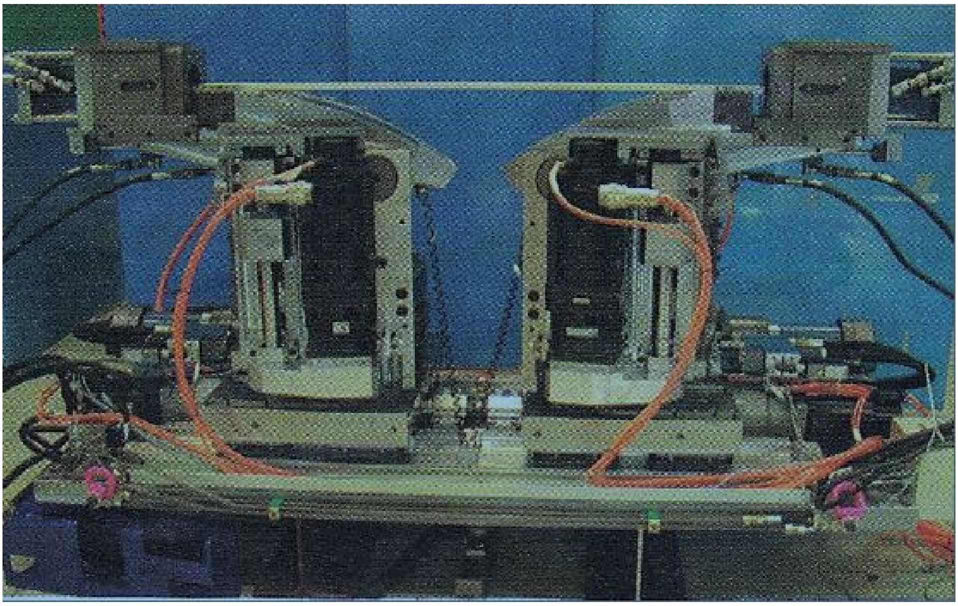

Figure 1.2: The 3DBM 2500-A (Welo & Holte, 2006).

Set-based concurrent engineering (SBCE) is a product development (PD) methodology where the product under development is divided into sub-systems, and sets of design solutions for each sub-system are developed in parallel. Through considerations regarding the entire system, the sub-system sets are narrowed throughout the development process with the aim of converging towards a globally optimised solution (A. Ward, Liker, Cristiano, & Sobek, 1995).

1.2 Objectives

This paper will present a case study of set-based concurrent engineering at an automotive parts manufacturer applied to a product development process of a novel gripping mechanism for the 3DBM.

A literature study of SBCE will be conducted. The tasks of the literature study are to identify:

- The SBCE principles of PD.

- A SBCE process model of PD.
- SBCE activities of PD.
- Previous SBCE case studies of PD.
- SBCE research gaps of PD.

The product development process will be structured and conducted according to the stages of the process model identified in the literature study and performed according to the principles and activities identified. Based on the experience from the case study, observations and suggestions regarding the research gaps will be presented. The suggestions should be unambiguous and new to the academic community as far as the literature study has managed to identify.

The case study will evaluate multiple system concepts and conclude with suggesting a novel gripping mechanism. The novel gripping mechanism will have design solutions which accommodates adjusting the gripping mechanism to new products at low cost. Technical drawings of the final concept's components will be presented.

Neglecting localised stress, the novel gripping mechanism should perform within the requirements:

- The novel gripping mechanism is capable of fixing the test profile subjected to a tensile force of $200kN$ with less than $5\mu m$ slippage in the test profile's point of minimum tensile translation.
- The natural frequencies of the novel gripping mechanism are not within the operating frequencies of actuators directly connected to the gripping mechanism.

The novel gripping mechanism will be analysed through a computer aided engineering (CAE) tool to evaluate whether these requirements have been met. Design considerations for the continued development of the novel gripping mechanism will be presented.

1.3 Scope

The product development process will conclude in an analysis by computer aided engineering (CAE) of the novel gripping mechanism. The analysis will regard the novel gripping mechanism in an assembled state under normal operating conditions, not including friction pattern. This implies firstly that the components are not expected to perform within the requirements individually, secondly that no requirements are set regarding the friction pattern, and lastly that the friction patterns influence on the novel gripping mechanisms performance will not be analysed.

The case study is a preliminary study preceding the development of the 3DBM. Therefore, the activities:

- Verification the novel gripping mechanism through physical testing.
- Determining tolerances of the novel gripping mechanism's components.

- Optimising the novel gripping mechanism to keep all localised stress below the yield point.

are all beyond the scope of this paper and will not be performed.

1.4 Research methodology

1.4.1 Case study

The case study will regard product development with the design methodology SBCE of an industrial gripping mechanism at an automotive parts manufacturer. Case study as a research method was chosen as the objective was open-ended. The author was co-located with an automotive parts manufacturer over a duration of four months, interacting with its employees and cooperating in the PD process. Literature studies and interviews of selected employees will be methods employed in order to aid the case study.

1.4.2 Literature study

According to Hart (1998, p. 1) ”a review of literature is important because without it you will not acquire an understanding of your topic, of what has already been done on it, how it has been researched, and what the key issues are”. According to Kitchenham and Charters (2007), the most common reasons for conducting systematic literature reviews is to:

- Summarise the existing empiric evidence in order to evaluate the object of study.
- Identify gaps in the existing research in order to suggest further research areas.
- Provide a background or framework in order to position further research.

Kitchenham and Charters (2007) arranges systematic literature reviews into three main phases: planning, conducting and reporting the review. Templier and Paré (2015) proposes a framework for the first two phases, which is evaluated to be applicable as the literature reviews will be reported as an integrated part of the paper. The framework is comprised of six steps:

- Formulating the problem
- Searching the literature
- Screening for inclusion
- Assessing quality
- Extracting data
- Analysing and synthesising data

Two main areas of research were considered to need investigation: the research methodology SBCE, as familiarity with the methodology was required to utilise the PD methodology and a framework of the PD process was required; and the influencing parameters in a bending operation, as knowledge of the bending operations was required for the PD.

The literature was searched for by the aid of the search engines ”Oria” and ”Google Scholar”, with broad, preliminary search terms. This preliminary search process was intended to identify the pioneering articles. The pioneering articles within the field were identified by backtracking the citations; articles were deemed to pioneer the field if written by particularly esteemed authors or cited to establish definitions or terms, trends within the field of research, or a structure commonly used.

This preliminary search process was intended to ensure that the primary sources were cited and to establish a structure for areas of literature to be reviewed. The subsequent search processes were more iterative and less restrictive with narrower search terms. The search process constituted results of the search engines, backtracking citations, investigated literature suggested by the search engines, and if literature reviews of the research areas were identified, they were used to obtain an overview of the field and its history and to identify further relevant sources. This iterative search process was intended to identify relevant articles; articles were screened for inclusion by investigating their abstract, and if deemed relevant, stored for subsequent investigation.

The literature study regarding the SBCE design methodology will be presented in Chapter 2. This literature study will be structured as to firstly present relevant definitions, secondly present the aim and characteristics of the design methodology, thirdly present its principles, and lastly present how to apply it in a practical PD process.

1.4.3 Interviews

The aim of the interviews conducted in this paper was to gain qualitative insight which might aid the development process. The interviewees were mostly experts in their fields and their knowledge might be tacit or recorded, and it might or might not be strictly factual, ranging from theoretical considerations to expert engineering judgement.

- Interviewee A is the team leader at the global centre of competence for aluminium extrusion and profile forming at the automotive parts manufacturer.
- Interviewee B is the tool design manager at the automotive parts manufacturer, and was involved in the development of the 3DBM 2500-A.
- Interviewee C is a tool designer at the automotive parts manufacturer, and will be involved in the development of the 3DBM.
- Interviewee D is a PhD-student at the Norwegian University of Science and Technology.
- Interviewee E is a PhD-student at the Norwegian University of Science and Technology

A very important aspect of the interviews was considered to be the exploratory aspect: to discover information not yet evident to the interviewer. Additionally, as the interviewer was co-located with the interviewees over a duration of four months, a more conversational, unstructured approach was deemed more advantageous than a structured approach, as too much structure might inhibit an interpersonal connection and therefore constrain the information made available. Based on these considerations, an unstructured interview approach was deemed the most appropriate.

The interviews were prepared by establishing with written key points what areas to be covered, but as the interviews were conducted there were very few constraints imposed on the interviewees. To communicate in a more effective manner, the interviews were performed in a highly visual manner, often with sketches or CAD models. The interviews were tape-recorded, and relevant information was transcribed. The interviews are transcribed in a verbatim manner to include the nuances of the statements. Transcribing the entirety of all interviews was considered too time-consuming and redundant, as the interviews were numerous, sometimes uncompressed or irrelevant due to their unstructured and visual nature. Transcriptions, along with the relevant sketches, are presented in Appendix A.

Chapter 2

Literature study of design methodology

2.1 Concepts related to SBCE

2.1.1 Prototypes and design cycles

Ulrich and Eppinger (2012, p. 291) defines a prototype as ”(...) an approximation of the product along one or more dimensions of interest” and prototyping as ”(...) the process of developing such an approximation of the product”. Houde and Hill (1997) states, ”By focusing on the purpose of the prototype – that is, on *what it prototypes* – we can make better decisions about the kinds of prototypes to build”. Further, prototypes can be classified as either physical or analytical (tangible or non-tangible) and as either comprehensive or focused (more or less detailed with regard to attributes approximated) (Ulrich & Eppinger, 2012). Houde and Hill (1997) suggests that a designer should:

- Define ”prototype” broadly, as prototypes should be used as a tool to provide answers to the questions explored in the least amount of time.
- Build multiple prototypes, as the prototypes in the early phases of development should be focused.
- Know your audience, as the required resolution and fidelity of prototypes vary among cultures. To some audiences, the designer may use prototypes to get feedback on evolving designs, while to others they may be used to indicate progress and direction.
- Know your prototype and prepare your audience, as the audience should be explained what the purpose of the prototype is (and what it is not).

Therefore, the definitions proposed by Ulrich and Eppinger (2012) will be used in this thesis as they emphasise the intent of prototypes without limiting the ways of achieving it.

Wheelwright and Clark (1994) states that for "(...) most development projects, the design-build-test cycle is the fundamental building block of effective problem solving". The design-build-test cycle consists of three phases: the design phase, where the problem to be solved is framed and ideas are generated; the build phase, where prototypes are constructed; and the test phase, where the prototypes are tested and evaluated (Wheelwright & Clark, 1994).

The Wright brothers – when designing the first machine capable of sustained, manned, heavier-than-air flight – diverged from this traditional design iteration cycle. They constructed tests with the aim of generating knowledge regarding distinct design features. This approach to the design iteration cycle would be termed test-before-design (Kennedy, Sobek, & Kennedy, 2013).

According to Kennedy et al. (2013), the key to test-before-design "(...) is to focus on designing the minimal tests that will yield sufficient data needed to close the identified knowledge gaps. This does not mean designing, building, and testing full system prototypes (which is time-consuming and expensive) but rather innovating ways to test (via prototype, simulation, or analysis) the critical elements of a system quickly and inexpensively". The knowledge generated was detailed in trade-off curves (ToCs), as illustrated in Fig. 2.1, where the relation between wing design parameters and performance established by the tests were visualised.

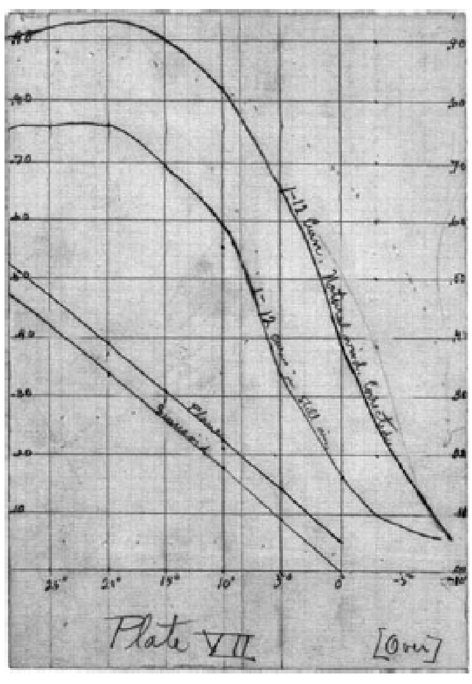

Figure 2.1: Trade-off curves of lift and angle of incidence for various surfaces, drawn by the Wright brothers (Kennedy et al., 2013)

2.1.2 Set-based design

The Wright brothers generated knowledge by exploring sets of designs to understand the design space, where the ”design space” may be defined as all design possibilities (Sobek, Ward, & Liker, 1999) and ”sets” simply refer to areas in the design space. This exploration may be termed ”mapping” this design space (Sobek et al., 1999).

A. C. Ward (1989) established set-based design (SBD) as a methodology in his dissertation regarding the design of a computer program aiming to aid the design process of mechanical systems. J. K. Liker, Sobek, Ward, and Cristiano (1996) differentiates SBD from point-based design (PBD) where ”(...) designers quickly develop a particular design solution – a point in the design space – then iterate from that starting point until they achieve a satisfactory solution”, whereas in SBD, as Sobek (1996) describes, ”The designer does not pick one idea but eliminates clearly unworkable ones and develops a subset of potential solutions of greater resolution before choosing”, as illustrated in Fig. 2.2.

After realising the advantages of describing design solutions as sets (A. C. Ward & Seering, 1989), Ward initiated an investigating of the widespreadness of set-based approaches in industry (A. Ward, 2007, p.VIII). He managed to identify a coherent, company-wide, set-based philosophy only at Toyota Motor Corporation (A. Ward et al., 1995).

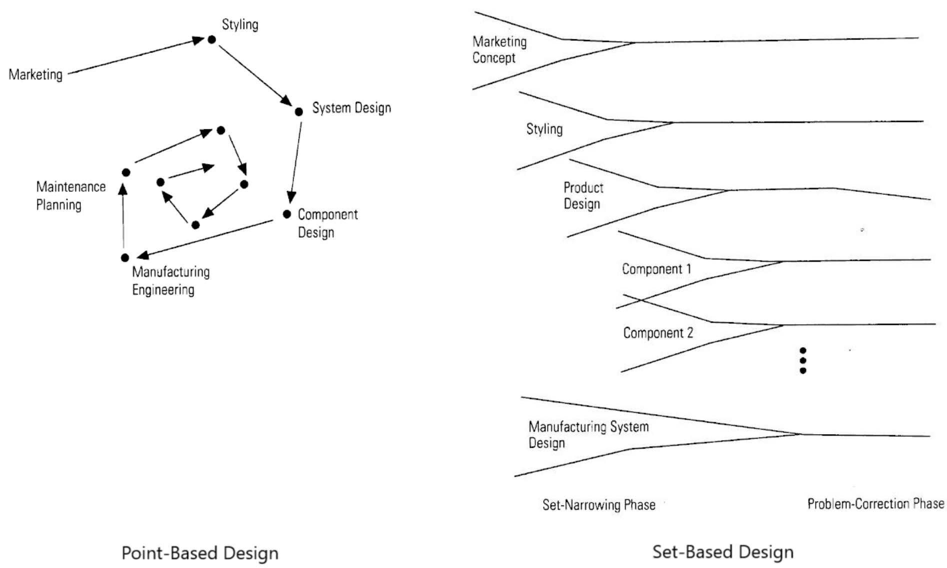

Figure 2.2: Comparison of point-based design and set-based design (adapted from (A. Ward et al., 1995)).

This new approach of the design iteration cycle generated knowledge and thus reduced rework later in the design process. Kennedy et al. (2013) used the term rework ”(...) to specifically mean the work that occurs when a prior decision that was assumed to be final for that project is changed because it was later found to be defective”, where a decision is final if "(...) the team does not have any reason to believe that the decision would need to change and therefore expects that development work can proceed assuming that decision will stand for the remainder of the project".

2.1.3 Lean

Womack (1990) had already identified Toyota Motor Corporation's lean philosophy: a production philosophy greatly deviating from the established methodologies in western industries. Womack and Jones (1996, p. 15-94) outlines five principles for lean thinking

- Specify Value
- Identify the Value Stream
- Flow
- Pull
- Pursue Perfection

The set-based approach is fundamental to lean manufacturing systems (Morgan & Liker, 2006, p. 51), and Walton (1999) characterise it as a fundamental framework for lean processes and lean product development (LPD). That being said, this literature study will not devote further attention to the lean philosophy.

2.1.4 Concurrent engineering

Additionally, Clark and Fujimoto (1991) had already identified Toyota Motor Corporation as one of the originators of concurrent engineering (CE). Winner, Pennell, Bertrand, and Slusarczuk (1988) coined the term concurrent engineering, defined as "(...) a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support", with the intent "(...) to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements". Winner et al. (1988) differentiates CE from sequential engineering (SE), stating that "In the sequential method, information flows are intended to be in one direction (...)", whereas "In the concurrent approach, information flows are bi-directional and decisions are based on consideration of downstream as well as upstream inputs". This is illustrated in Fig. 2.3.

2.2 Main characteristics of SBCE

A. Ward et al. (1995) identified a design methodology at Toyota Motor Corporation combining an SBD approach with the CE practices, which they termed set-based concurrent engineering. Sobek (1996) describes this methodology as a process where "Engineers reason and communicate about sets of ideas, not one idea at the time". Sub-systems are

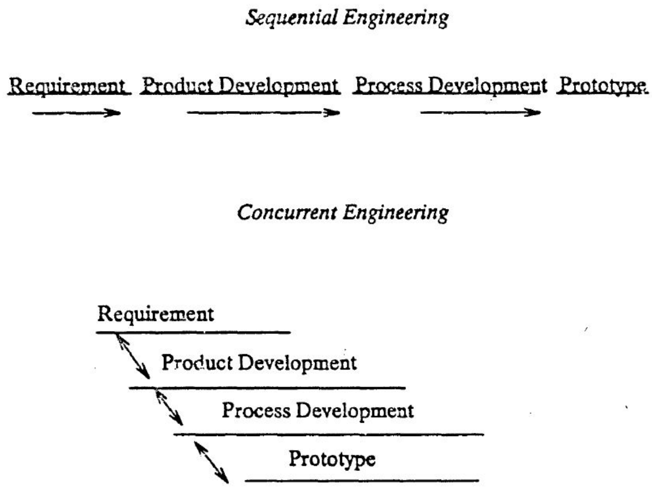

Figure 2.3: Comparison of sequential engineering and concurrent engineering (Winner et al., 1988).

developed concurrently, and sets of design possibilities are narrowed based on newly acquired knowledge. As the development process advance, the sets converge towards an intersection of all sub-systems (A. Ward et al., 1995). This is illustrated in Fig. 2.4.

J. Liker, Sobek, Ward, and Cristiano (1996) argues that effective concurrent engineering requires a set-based approach. A. Ward et al. (1995) argues that the intersection of sets will converge towards a robust solution with reduced rework in the development process (A. Ward et al., 1995), a major contributor to Toyota's few engineering changes (Morgan & Liker, 2006, p. 50).

Sobek et al. (1999) identified three main principles in SBCE, to which Khan, Al-Ashaab, Doultsinou, et al. (2011) supplemented two (the latter two in the listing). The main principles of SBCE are:

- Mapping the design space
- Integration by intersection
- Establishing feasibility before commitment
- Creating and exploring multiple concepts in parallel
- Strategic value research and alignment

Additionally, Khan, Al-Ashaab, Doultsinou, et al. (2011) structures SBCE into phases in what they call "the baseline model". The baseline model is a structure of SBCE phases and activities proposed in an initiative called the "Lean Product and Process development" (LeanPPD) project in the aim of establishing a lean PD model applicable to European industry (Al-Ashaab, Flores, et al., 2010; Al-Ashaab, Shehab, et al., 2010). Extensive research has been devoted to establishing such a model (Khan, 2012; Khan, Al-Ashaab,

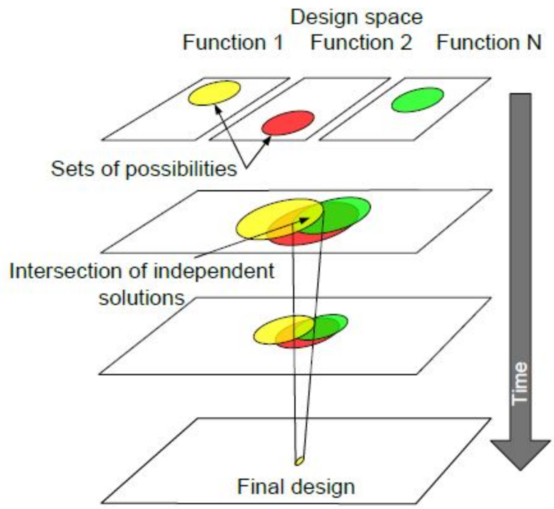

Figure 2.4: Intersection of sets in Toyota's development process (D. Raudberget, 2011).

Shehab, et al., 2011; Sorli et al., 2012), but this literature study will regard the baseline model separate from the LeanPPD project. The baseline model establishes five stages with related activities:

- Value research
  - Classify project type
  - Explore customer value
  - Align with company strategy
  - Translate customer value to designers
- Map design space
  - Identify sub-system targets
  - Decide on level of innovation to sub-systems
  - Define feasible regions of design space
- Concept set development
  - Pull design concepts
  - Create sets for each sub-system
  - Explore sub-system sets: prototype and test
  - Capture knowledge and evaluate
  - Communicate set to others
- Concept convergence

  - Determine set intersections
  - Explore system sets
  - Seek conceptual robustness
  - Evaluate sets for lean production
  - Begin process planning for manufacturing
  - Converge on final set of sub-system concepts

- Detailed design
  - Release final specification
  - Manufacturing provide tolerances
  - Full system definition

This is illustrated in Fig. 2.5. Interaction with customers and involvement of suppliers are actions which should be performed throughout the entire process. The principles and the process are tightly connected and will be explained concurrently.

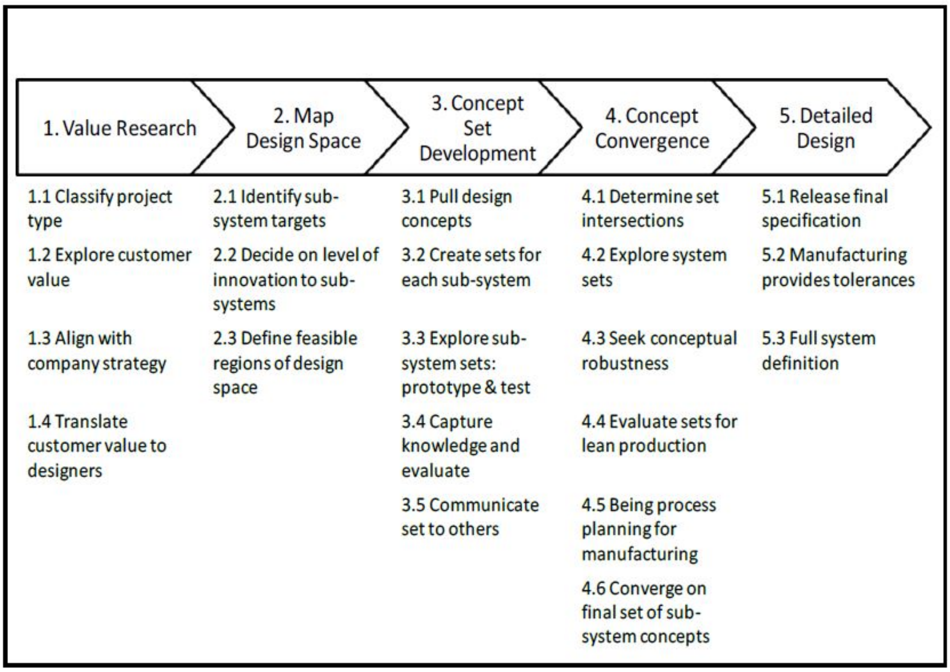

Figure 2.5: The baseline model (Khan, Al-Ashaab, Doultsinou, et al., 2011).

2.3 The baseline model

2.3.1 Value research

Strategic value research and alignment is one of the main principles in SBCE. The project type is classified in terms of level of innovation incorporated, and aligned with the strategy of the customer and their project portfolio. This is to identify how the customer may take strategic advantage of the project, increasing its customer value. Further, customer value should be identified and communicated to the PD team to function as a guideline throughout the project.

2.3.2 Map design space

Mapping the design space is one of the main principles in SBCE. The system is structured into sub-systems, and the level of innovation for the system and sub-systems are planned, as well as their essential characteristics. The level of innovation may be mapped with an innovation classification chart, as illustrated in Fig. 2.6.

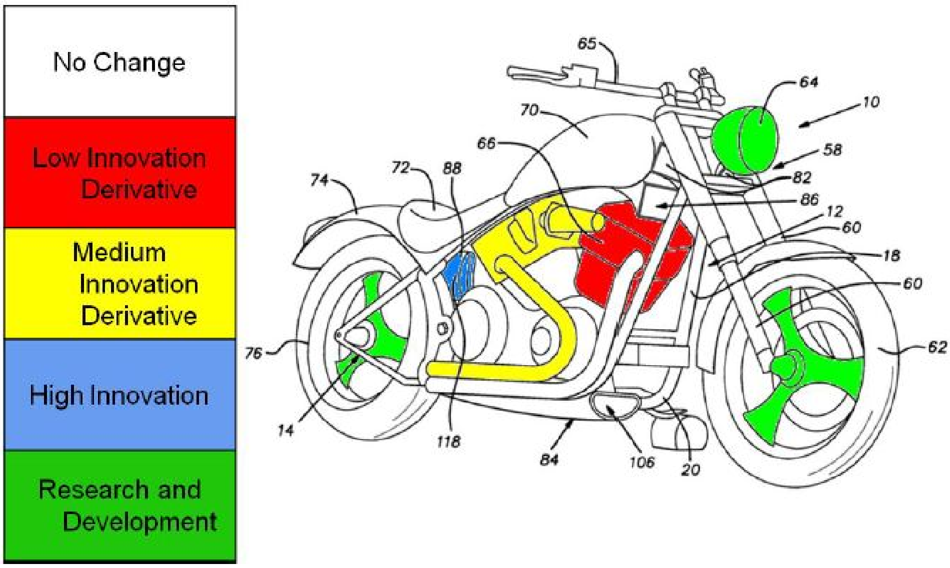

Figure 2.6: Innovation classification chart (Khan, 2012).

At the beginning of this stage, the various design solutions are boundless. These sets of design possibilities are narrowed throughout the development, in which the mapping of the design space is the starting point. The sets of design possibilities are narrowed by defining feasibility regions – primary design constraints – based on experience, testing or analyses functioning as a guide for what part of the design space should be aimed for or avoided (Sobek et al., 1999).

Mapping the design space is directly related to another main principle: establishing feasibility before commitment. This is achieved by narrowing sets gradually while increasing detail, enabling an evaluation of all possible designs and over-all system optimisation. The process is controlled by managing uncertainty at process gates in the form of prototypes integrating the various sub-systems (Sobek et al., 1999).

Information regarding the interaction between various sub-systems is given by the sets, which makes it important to stay within sets once committed.

2.3.3 Concept set development

Concept set generation

When generating sub-system sets, knowledge should be captured by extracting concepts from previous projects, the R&D department, or competitors products, and novel concepts should be generated through brainstorming (Khan, Al-Ashaab, Doultsinou, et al., 2011).

The sets must be robust in the sense that it must contain at least one workable solution; there are several ways of ensuring that the sets are robust throughout the PD process:

- Including a conservative solution as a back-up may help the developers dare to explore innovative concepts while maintaining a robust set (Sobek et al., 1999).
- Designing sets to be functional regardless of external parameters, and thus compatible with all sets of interacting sub-systems (Sobek et al., 1999).
- Exploring a large number of solutions and strategically eliminating those deemed incompatible (D. Raudberget, 2011).

Concept set exploration

Creating and exploring multiple concepts in parallel is one of the main principles in SBCE. These sets are narrowed according to the principles of test-before-design; tests of critical aspects of the sets are constructed to generate knowledge, and clearly infeasible sets are eliminated. The elimination process should ideally begin with ”low-hanging fruit” – solutions easily evaluated with a large number of related sets which can be eliminated if the solution is deemed incompatible.

Within these sets of design possibilities, trade-offs are explored through evaluating various sets of design by establishing a relationship between parameters. According to Sobek et al. (1999), ”Whenever possible, engineers abstract from prototype data to establish mathematical relationships between design parameters and performance outcomes or use test data from a number of test pieces and interpolate relationships”. Communicating designs are performed by communicating the sets of design possibilities, often in bounded or open-ended intervals. This communication should regard entire sets and preferably be performed visually. ToCs and decision matrices (Morgan & Liker, 2006) are commonly used tools for visual communication in SBCE, as illustrated in Fig. 2.7.

Trade-off curves play an important part in capturing and visualising knowledge in SBCE. Araci, Al-Ashaab, and Maksimovic (2016) emphasise the necessity for a knowledge-based environment for successful implementation of SBCE, and Maksimovic, Al-Ashaab, Sulowski, and Shehab (2012) emphasise the necessity to consider how to

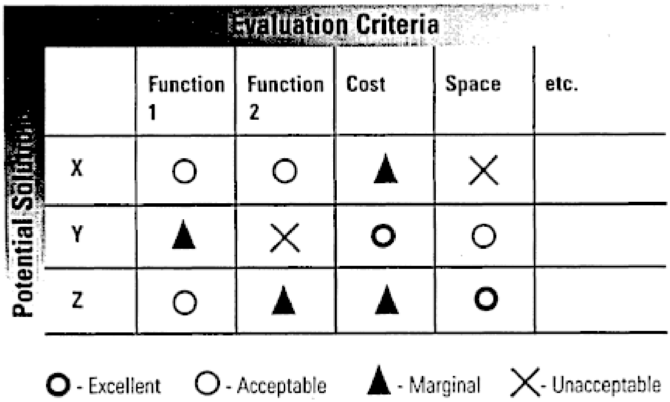

Figure 2.7: Decision matrix (Sobek et al., 1999).

identify, capture, represent and re-use the knowledge to visualise knowledge in ToCs optimally. Araci, Al-Ashaab, and Maksimovic (2015) classifies ToCs into knowledge-based and math-based. Araci, Al-Ashaab, Garcia Almeida, and McGavin (2016) propose a structured process to develop math-based ToCs.

2.3.4 Concept convergence

During the "concept convergence" phase, the sub-systems are integrated through evaluation of the intersection of feasible sets, converging toward a final set of each sub-system. Integration by intersection is one of the main principles in SBCE. If each sub-system is separately being optimised, the overall product may not be. Morgan and Liker (2006, p. 50) argues that "(...) to focus on system *compatibility* before individual design *completion*" is fundamental to the set-based approach. For this integration to be successful, it is essential to stay within sets when committed.

Consider the example of an automobile; the engine and brakes are interdependent and must be compatible, and the development of these components should seek a global optimum. The knowledge of sub-system intersection must be made explicit and communicated nominally as sets rather than fixed values. Further, in order to maintain flexibility to optimise the system, the constraints should be kept to a minimum and delayed until needed.

A part of this global optimisation process is to explore system sets through prototyping and testing, and consider aspects regarding production processes and manufacturing in the design.

2.3.5 Detailed design

During the "detailed design" phase, final specifications are defined and tolerances are set by manufacturing, and the full system is defined.

2.4 Research gaps

2.4.1 Concept set generation framework

An absence of a structured framework for the generation of sub-system sets in SBCE was identified. Because of this, the literature study aimed to identify a point-based concept generation framework and to adapt elements of this to the baseline model. Ulrich and Eppinger (2012) propose a five-step process for concept generation in point-based PD:

- Clarify the problem – decomposing the problem into critical sub-problems with the aim of acquiring a deeper understanding of it.
- Search externally – interviewing lead users and/or experts, as well as searching for patents, literature and existing solutions, with the aim of generating concepts.
- Search internally – brainstorming, either as an individual or a group, preferably by the use of visual or physical media. The aim is to generate numerous ideas, regardless of feasibility.
- Explore systematically – structuring generated ideas into a concept classification tree, as illustrated in Fig. 2.8. A concept classification tree is claimed to provide four benefits: enabling pruning of less promising branches; identification of independent approaches to the problem; exposure of inappropriate emphasis on certain branches; and refinement of the problem decomposition for a particular branch (Ulrich & Eppinger, 2012, p. 131-133). Further, structuring the concepts of each sub-system into a concept combination table, as illustrated in Fig. 2.9.
- Reflect on the solutions and the process – subsequent reflection may improve the process, aiding the current or future projects.

In order to adapt the five-step process into the baseline model, elements of the five-step process compatible with the principles and activities of SBCE were identified. The compatible elements identified are presented in Table 2.1.

2.4.2 Discussion regarding design fixation

A research gap was identified regarding a discussion of design fixation in relation to extracted concepts in SBCE. Jansson and Smith (1991) defines design fixation as ”(...) a blind adherence to a set of ideas or concepts limiting the output of conceptual design”.

2.4.3 Computer tools

According to Al-Ashaab et al. (2013), one of the main research gaps at the time was how to employ computer tools in product development in SBCE. In an industrial trial of SBCE, the designers shifted towards a design-by-simulation philosophy, replacing the physical prototypes (Madhavan, Shahan, Seepersad, Hlavinka, & Benson, 2008). One of Toyota's principles regarding computer tools is to adapt the technology to the process (J. K. Liker & Morgan, 2006). Toyota revises the computer aided design (CAD) models according

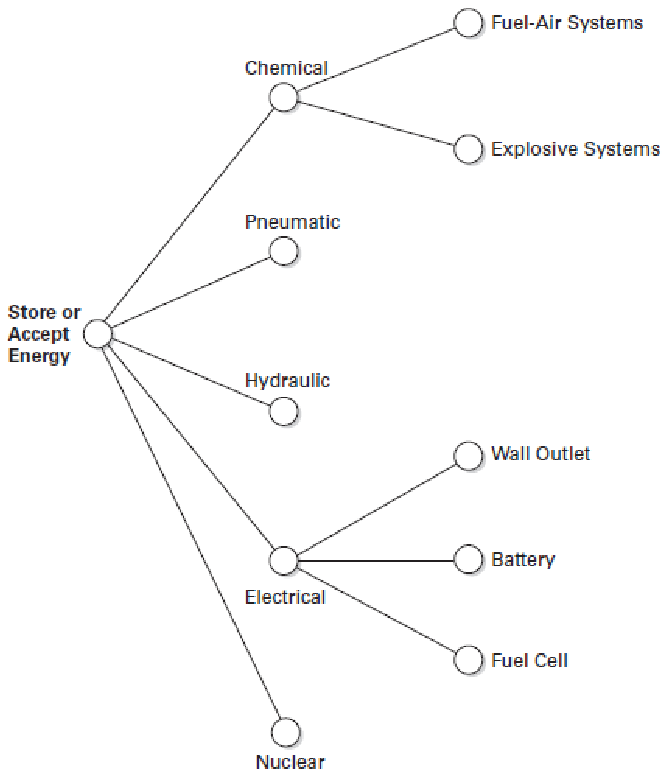

Figure 2.8: The concept classification tree (from an example of energy source concepts for a hand-held roofing nailer) (Ulrich & Eppinger, 2012, p. 132).

Convert Electrical Energy to Translational Energy	Accumulate Energy	Apply Translational Energy to Nail
Rotary motor with transmission	Spring	Single impact
Linear motor	Moving mass	Multiple impacts
Solenoid		Push nail
Rail gun		

Figure 2.9: The concept combination table (from an example of a handheld roofing nailer) (Ulrich & Eppinger, 2012, p. 134).

The five-step process	Compatible element in SBCE
Clarify the problem step	Mapping the design space
Search externally step	Pulling design concepts
Search internally step	Generate design concepts
Explore systematically step	Making knowledge explicit (Sobek et al., 1999)
The classification tree	Concept structure of A. C. Ward and Seering (1993)
Pruning of branches	Elimination of ”low-hanging fruit” (D. Raudberget, 2011)
The concept combination table	Concept combination calculations of Al-Ashaab et al. (2013)
Reflect on the solutions and the process step	Lean principle of pursuing perfection (Womack & Jones, 1996, p. 25)

Table 2.1: Elements of the five-step process compatible with SBCE

to the physical prototypes (Sobek et al., 1999). The CAD models of all feasible designs are stored in a database (Sobek, 1996) and relevant models are distributed to suppliers to communicate visually early in the process (A. Ward et al., 1995).

To aid the implementation of SBCE, Ford and Sobek (2005) developed a simulation tool to aid PD management by visualising the effects of decisions within an SBCE framework. Akaberi (2011) developed an awareness-educational business game to introduce SBCE concepts to its players, and Gray and Singer (2015) developed a tool to aid set-based communication.

To aid designers in set-based development projects, computer tools have been developed (D. Raudberget, 2011). Additionally, CAD/CAE tools have been adapted into an SBCE process, for example by performing multiple analyses over a range of the design space. This has been done either by combined ToCs derived from technology development with CAE (Levandowski, Forslund, & Johannesson, 2013) or to assign weighting to areas of the design space preferred by the designer, an adaption of SBD termed Preference Set-Based Design (PSD) (Inoue, Nahm, Okawa, & Ishikawa, 2010; Nahm & Ishikawa, 2006). A different approach has been to develop a computer tool to establish couplings between functions in CAD models in order to eliminate infeasible sets (D. S. Raudberget, Landahl, Levandowski, & Müller, 2016; D. S. Raudberget, Michaelis, & Johannesson, 2014).

2.4.4 Case studies

According to Al-Ashaab et al. (2013), one of the main research gaps regarding SBCE at the time was ”the limited number and variety of case studies where SBCE is implemented in industry”.

In the automotive industry, Toyota Motor Company is an obvious example of an industrial application of SBCE. Additionally, J. K. Liker and Morgan (2011) transformed the automotive body development process of Ford Motor Company – an automotive company – into an LPD process, ”(...) helping to bring to market a record number of products that helped fuel a rebuilding of the company to financial success”, according to the authors.

Al-Ashaab, Howell, Usowicz, Hernando Anta, and Gorka (2009) evaluated the automotive electronic/software systems development at Jaguar Cars – an automotive company – and proposed a methodology based on a combination of SBCE and the software development methodology the V-model.

Oosterwal (2010) presented the implementation of LPD techniques into Harley-Davidson's – a motorcycle manufacturing company – PD process. The author describes the realisation that ”Set-based development is not intended to be the simultaneous parallel development of multiple design options to reduce risk by increasing odds. In fact, set-based development is a carefully orchestrated development process that exploits the learning principles of experimental learning cycles to explore the limits of a design to understand the risks” (Oosterwal, 2010, p. 182-183).

D. Raudberget (2010) presented a case study applying SBCE in the PD process in four companies: an electronic systems developer, a graphic industry products developer, an automotive supplier and a manufacturer of heavy trucks and engines. The companies reported improvements in level of innovation, product cost, and product performance. Ammar, Hammadi, Choley, Barkallah, and Louati (2018) applied SBCE in the development of an electronic throttle body. This was intended to identify possible complications in implementing SBCE in PD of mechatronic systems.

Aiming to address the complexity of implementing SBD in companies, Ström, Raudberget, and Gustafsson (2016) presents a simplified design methodology Instant Set-Based Design (ISBD) applied to eight case studies – five of which with industrial applications. Ström et al. (2016) claims ISBD is applicable to mechanical design problems, simplifying the implementation of SBD in industry.

Bernstein (1998) assessed the “set-basedness” of the aerospace industry, managing to identify several set-based techniques utilised, but no application of set-based concurrent engineering as a complete PD process. Al-Ashaab et al. (2013) incorporated the SBCE principles defined by the LeanPPD process model to transform the existing PD process of Rolls-Royce – an aerospace company – into a lean environment, applied in a case study of a helicopter engine.

The U.S. Department of Defence has had several initiatives to case studies of utilising set-based design for PD within the Navy and Marine Corps (Singer, Doerry, & E. Buckley, 2009): Mebane, Carlson, Dowd, Singer, and Buckley (2011) presented a case study of SBD applied in the developed a ship-to-shore connector, Doerry et al. (2014) in the development of an amphibious combat vehicle, Garner et al. (2015) in the development of a small surface combatant, and – according to Chan, Hays, Romas, Weaver, and Morrison (2016) – a large displacement unmanned underwater vehicle is under development. Based on these case studies, Chan et al. (2016) provided guidelines for how to implement set-based design into the U.S. Department of Defence's acquisition framework. Further, in the development of the ship-to-shore connector, a software tool for set-based communication developed by Gray and Singer (2015) was utilised.

Within the oil and gas industry, Madhavan et al. (2008) converted the existing design process of Schlumberger – a developer of oilfield tools and services – into a set-based design process, applied in a case study of the design of a downhole module. Madhavan et al. (2008) argued the decomposition of the design problem to be one of the main benefits of the set-based approach, aiding in defining coupled variables and exploring interdependencies of activities on the system and sub-systems level.

Flisiak et al. (2016) applied the LeanPPD process model to a case study of a surface jet pump, in collaboration with Caltech Ltd. – a developer and manufacturer of oil and gas production process enhancement solutions. Based on this case study, Maulana et al. (2017) discuss the potential tangible benefits of SBCE in this application. The authors conclude that SBCE in the case study increases the success rate from 33% to 96%, while decreasing the risk of failure designs from 20% to 0.8%. Further, Araci et al. (2017) discussed how the application of ToCs aided the development of the case study by providing and visualising knowledge.

Within the architecture engineering construction industry, Parrish (2009) applied SBD in case studies regarding the selection of reinforces steel configurations, and argued the methodology's applicability in the industry.

2.5 Structure of the case study in this paper

The product development of the gripping mechanism will be conducted according to the principles of SBCE as presented by Sobek et al. (1999) and Khan, Al-Ashaab, Doultsinou, et al. (2011). The product development process will be structured according to "the baseline model" as presented by Khan, Al-Ashaab, Doultsinou, et al. (2011). This paper will be structured in the stages presented in this model: value research, map design space, concept set development, concept converegence and detailed design.

- In the *value research* stage, the strategy of the automotive parts manufacturer will be investigated through the company's documentation and interviews with its employees, in the aim of aligning the project with the company's strategy. Further, as J. Liker et al. (1996) emphasised the importance of a set-based approach in true concurrent processes, the various multidisciplinary trade-offs in the automotive parts manufacturer's PD process will be investigated in the aim of establishing customer value of the design methodology. This requires an understanding of the value chain, and thus the value chain wherein the 3DBM is to operate will be investigated. This investigation will additionally aim to establish the tolerance variations along the workstream, establishing customer value of the bending operation as well as mapping product variations the gripping mechanism must accommodate.

- In the *mapping the design space* stage, the 3DBM 2500-A will be presented, along with its machine elements and bending operation. The gripping mechanism of the 3DBM will be structured as a sub-system of the 3DBM, which will be structured into further sub-systems – the importance of which emphasised by Madhavan et al. (2008). The level of innovation in these sub-systems will be established through interviews, presented visually in an innovation classification chart, as presented by Khan (2012). Further, feasibility regions within the design space will be established through the company's documentation and interviews with its employees.

- In the *concept set development* stage, sub-system concepts will be generated and explored. As the literature study failed to establish a clear framework for creating sets for each sub-system within the SBCE methodology, the point-based five-step process presented by Ulrich and Eppinger (2012) will be adapted to the baseline model, as several aspects are compatible.

- The *clarify the problem* step will have been conducted in the *mapping the design space* stage.
- The *searching externally* step regarding searching for existing solutions is comparable to pulling design concepts. Further, lead users and experts will be interviewed, and a literature search regarding parameters influencing bending operations will be conducted.
- The *searching internally* step will consist of an individual brainstorming session.
- The *explore systematically* step will consist of the structuring of concepts of each sub-system in separate concept classification trees. The concepts of each sub-system will be further structured in a concept combination table. The system concept amount will be calculated as presented by Al-Ashaab et al. (2013).
- The *reflect on the solutions and the process* step will be performed, but not reported. Sobek et al. (1999) emphasise the necessity of including at least one conservative solution within the sets; the gripping mechanism of the 3DBM 2500-A will serve as a backup solution, possibly along with additional solutions established and thoroughly tested at the automotive parts manufacturer.

The exploration of sub-system sets will consist of an initial pruning of the branches of the concept classification trees, or – following the analogy of as D. Raudberget (2011) – eliminating the "low-hanging fruit". The prototyping will be conducted according to the principles of test-before-design presented by (Kennedy et al., 2013) – the importance of which emphasised by Oosterwal (2010). At this stage, prototyping will be of low resolution, mainly relating design parameters to functionality in the aim of producing ToCs. The ToCs' importance in SBCE is discussed by Sobek et al. (1999) and Araci et al. (2017).

- In the *concept convergence* stage, the remaining concepts will be prototyped in greater resolution, as suggested by Sobek et al. (1999). As the literature study uncovered a lack of applicable software solutions, an effort will be to investigate the applicability of various solutions. This will mainly regard how to adapt CAD/CAE to accommodate a set-based approach.

  Flexible assembly models and 3D printed models will function as integrating prototypes as discussed by Sobek et al. (1999), parameter studies in various resolutions will be conducted to test design parameters before integrating in the design. The intersection of sub-systems will be investigated, as well as similarities among the concept within each sub-system.

- In the *detailed design* stage, a complete CAE analysis of the system will be conducted in the aim of testing the final system. Technical drawings of the components will be produced and presented. Determining tolerances of the components is beyond the scope of this paper and will not be performed.

Chapter 3

Value research

3.1 Presentation of the customer

The customer is an automotive first-tier supplier and a world-leading automotive parts manufacturer of high-performance crash management systems for automobiles by extruded aluminum. Examples of some of the systems produced by the customer are presented in Fig. 1.1. Fig. 3.1 illustrates three products constructed by aluminum extrusions bent by the 3DBM 2500-A.

According to their own figures from 2016 (Benteler Automotive, 2018) (thus susceptible to being biased and outdated, but sufficient as an indication) the customer has a net sale of approximately 200 million EUR and were forecasted to produce approximately 5 million parts that year. The customer is a subsidiary of an international holding company. Located in Norway, the customer employs approximately the full-time equivalent of 510 employees. The customer has competence and technology to apply casting, extrusion, stretch-bending and forming, heat treatment, machining, and automatic welding and assembly. Additionally, the customer prototype, develop and test tools, products and production processes.

3.2 Classification of project type

The customer develops component-specific tools to produce the automotive components. Interviewee A (interview A.8) stated that the customer has to ”Reduce the tool cost [in order] (...) to survive in the future [as] More and more customers are not willing to pay so much for the tools any more”. Component-specific tools are one of the factors reducing the 3DBM 2500-A’s flexibility significantly, as incorporating new products necessitates 30-60 hours of tool design, 8-10 weeks for tool production, and a tool investment of 0.4-0.6 MNOK (Benteler Automotive, 2005).

When questioned regarding the automotive parts manufacturer’s strategy for reducing tool cost, interviewee A stated that the strategy was ”(...) continuous improvement, but we

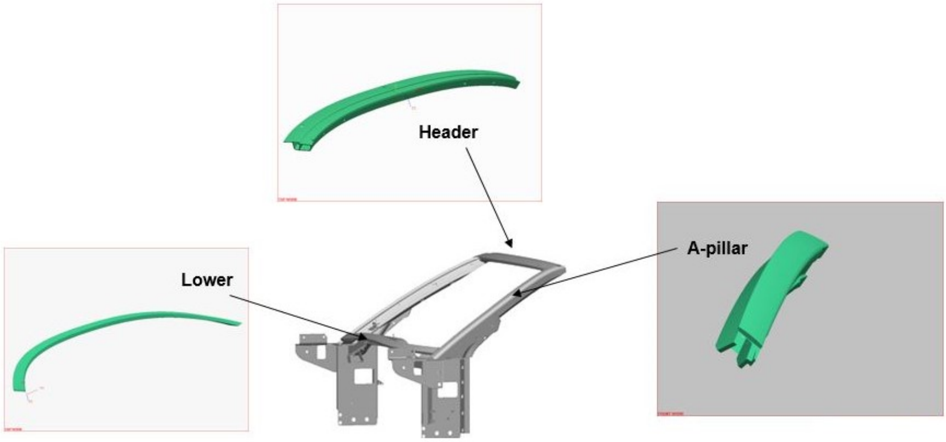

Figure 3.1: Automotive components of extruded aluminum bent by the 3DBM 2500-A (Benteler Automotive, 2018).

also necessitate some radical steps if we are supposed to manage it – the two-dimensional stretch bending machine is actually radical compared to what we have had before. Then you move from a pressing tool to a much simpler setup, but with the same function. Well, partly: you can bend it, but you don't get to do anything else". The two-dimensional stretch bending machine (2DBM) is a similar machine to the 3DBM but limited to bending in two-dimensions. Similarly to the 2DBM, the 3DBM will form automotive components that don't require much forming else than bending. Furthermore, the interviewee stated that the customer aimed towards making the process "(...) as lean as possible" and that they include certain elements of lean PD, but not SBCE.

The project will concern an innovative SBCE product development of a gripping mechanism for the 3DBM. The project will be a preliminary study predating the actual development of the 3DBM. The design solutions of the gripping mechanism will be developed under the assumption that all aspects of the 3DBM except its gripping mechanism will be constructed with the design solutions of the 3DBM 2500-A. Any interaction and assumption regarding the rest of the machine during the PD must be clearly established through interviews.

3.3 Customer value through concurrent engineering

Automotive parts manufacturers typically specialise in certain component types, depending on their expertise and production process, which they aim to win contracts to produce for various automotive manufacturers. These contracts are competed for in a nomination process, where the automotive manufacturers distribute technical specifications of an automotive part, to which the automotive parts manufacturers presents a concept with a product description, documentation of requirements, and price. If the contract is won, the automotive manufacturer and the automotive parts manufacturer commence serial development and verification of the product before its release for serial production. This process is illustrated in Fig. 3.2.

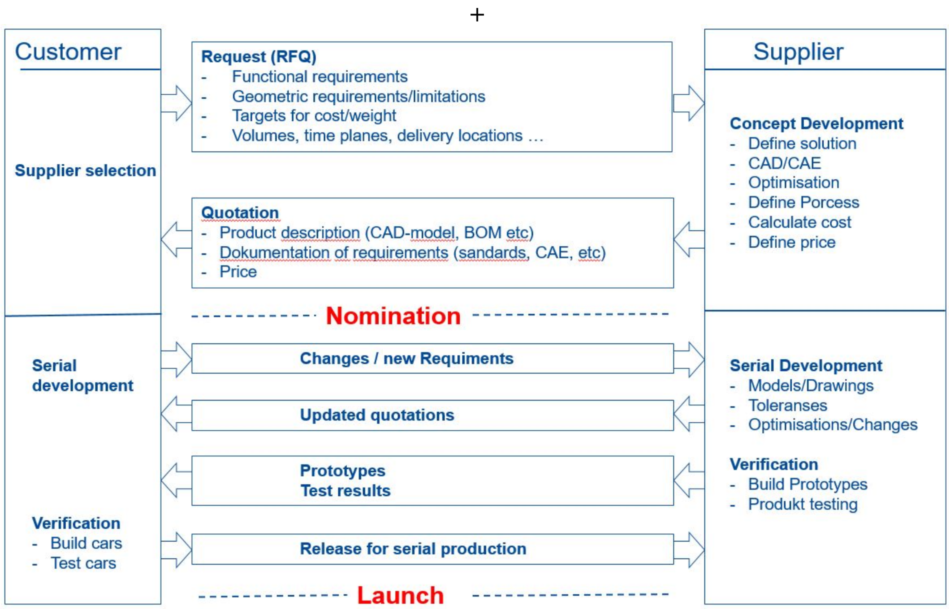

Figure 3.2: The nomination process (the automotive parts manufacturer is termed "supplier" and the automotive company is termed "customer" in this illustration) (Benteler Automotive, 2018)

According to Welo and Paulsen (2001), the requirement of a structural component posed by the automotive manufacturer can be divided into four categories:

- The functional category includes packaging, surface and mounting location, attachments, weight, and dimensional tolerances.
- The structural category includes local and global strength and stiffness.
- The dynamic category includes crashworthiness, mobility, natural frequency and modes, noise, vibration and harshness.
- The durability category includes corrosion, fatigue, temperature exposure, exposure to fluids, salt, etc.

As long as these requirements are met, the automotive parts manufacturers are free to engineer the part to fit their production process (Paulsen, 2018c). The freedom of design, limited to the specifications, enables the automotive parts manufacturers with an efficient and capable production process to deliver parts which outperform their competitor's in terms of quality and/or price, and to advocate design solutions. The customer tailors all aspects of their products and processes in order to attain competitiveness, balancing trade-offs through concurrent engineering. The engineering value chain at the customer is presented in Fig. 3.3.

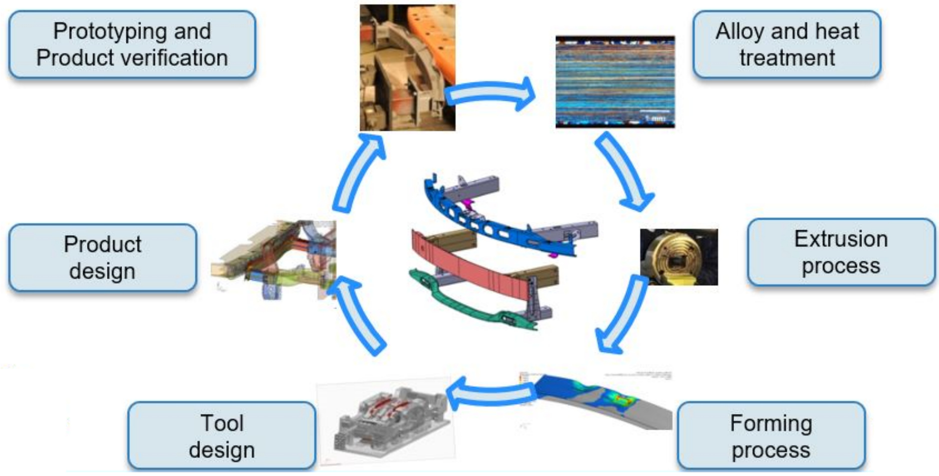

Figure 3.3: The engineering value chain at the automotive parts manufacturer (Benteler Automotive, 2018)

The customer must provide documentation of their solutions through CAD/CAE. In order to provide compatibility, there is often a requirement from the automotive manufacturers that the automotive parts manufacturer's digital models must be produced in the same CAD tool – sometimes even the same finite element method (FEM) tools – as the automotive manufacturer employ themselves (Welo & Paulsen, 2001). Therefore, the customer must design their components in different computer tools depending on the automotive manufacturer.

The value of automotive components is determined by the market, while the cost is mostly determined by the raw materials and the production methods. Thus, the revenue can be increased through material choice and cost-effective production. Material constitutes up to 80% of the cost of the components (Benteler Automotive, 2018), and as aluminum has a base material price more than four times higher than traditional steel (MetalMiner, 2018), it is crucial to utilise the positive factors of aluminum extrusions to reduce cost and/or increase value (Benteler Automotive, 2018). Interviewee A (interview A.14) stated that the advantage of extrusions is "That you can integrate functions that you cannot in a plate". Some of the advantages of aluminum as the material choice is:

- The formability enables unique design solutions (for example, extrusion) and effective production.
- The low weight-to-strength ratio.
- The recyclability to reuse or sell material scrap from production
- The corrosion resistibility to increase the value of the component.

3.4 Customer value through tolerance control

The bending process takes part in a bigger value chain. A typical processing route for formed aluminum components is illustrated in Fig. 3.4. All of these process steps consists of manipulation of material and/or geometrical parameters, which are delivered downstream the workflow, optimally within set tolerance limits. It is crucial for the quality of the products to have reliable machines at each process steps that deliver within tolerance limits as narrow as possible. The width of these tolerance limits, and the variations within them among the various workpieces, determines the accuracy of the overall production process.

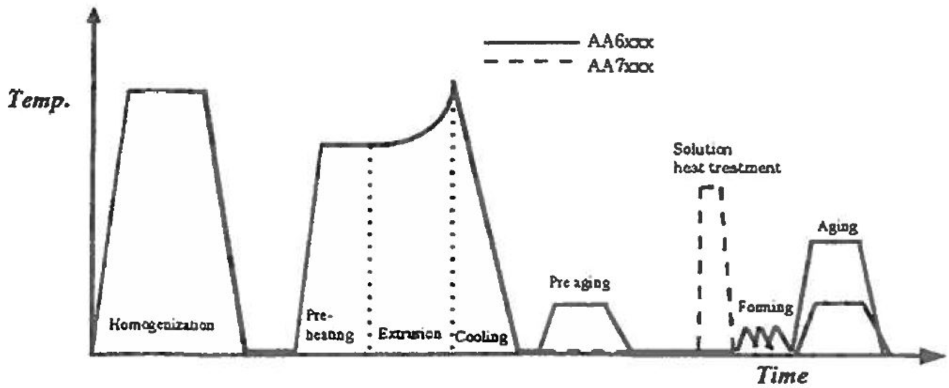

Figure 3.4: Typical processing route for formed AA6xxx and AA7xxx components (Welo & Rizk, 1997).

A typical value chain for an aluminum component contains an increasing product complexity, number of process quality variables, and significance of tolerances (with accumulative effect) along the workstream (Welo & Paulsen, 2001). This is illustrated in Fig. 3.5. The deviation of the desired and actual parameters after a process step can inflict further deviations downstream, which conflict with the fact that the significance of tolerances increases along with the product complexity.

Certain process steps function as compensation for the accumulating deterioration of tolerances. Among these are heat treatment processes and the bending operation. The heat treatment minimises material deviations. The heat releases residual stresses in the material and rearranges microstructures within the material in a similar manner for all workpieces. The bending operation minimises geometrical deviations (along with certain material deviations) (Paulsen, 2018c). The bending subjects the workpieces to similar deformation. Interviewee A (interview A.8) stated "What have made our methods competitive is that we have managed to remove variations from extrusions through forming – for example through stretch bending – so we are not required to calibrate and adjust the profile; they usually fit at once if they are supposed to be welded onto others".

If an automotive parts manufacturer delivers components of low quality, the repercussions may be plenty. It may be economically burdened directly, as the automotive manufacturer will demand the automotive parts manufacturer to retrieve and replace the

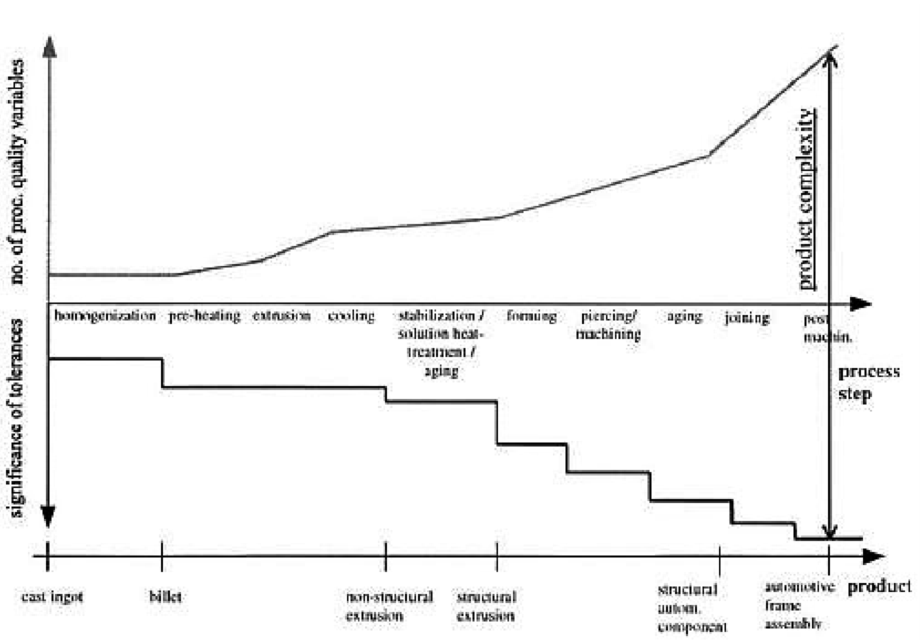

Figure 3.5: Accumulation of product complexity, process quality parameters and significance to tolerances along the value chain of a typical aluminum component (Welo & Paulsen, 2001).

delivered parts, or even be economically responsible in the event of a recall of automobiles. In addition to this, it will damage the automotive part manufacturer's reputation (Paulsen, 2018c).

3.5 Trade-offs and tolerances in customer's value chain

3.5.1 Billet acquisition

The customer buys billets of the desired material within explicit tolerance limits. The main aluminum alloys for extruded automotive components are the AA6xxx and the AA7xxx. These alloys have comparable characteristics, as illustrated in Fig. 3.6. This section will regard the value chain of AA6xxx alloys up until forming, as these are the alloys to be bent by the 3DBM.

The product design should be optimised so that the final design behaves within requirements with minimised cost regarding the material (alloy and amount) and maximised efficiency in the production process, as indicated in Fig. 3.7. The material price and processing costs are generally higher with increasing yield strength.

Ductility is needed both during the process for formability and in the finished component for crash performance. This poses constraints on material choice and material property manipulation processes. Ductility for increased crash performance is provided by a material with gradually reduced stress at fracture strain, not simply the elongation at

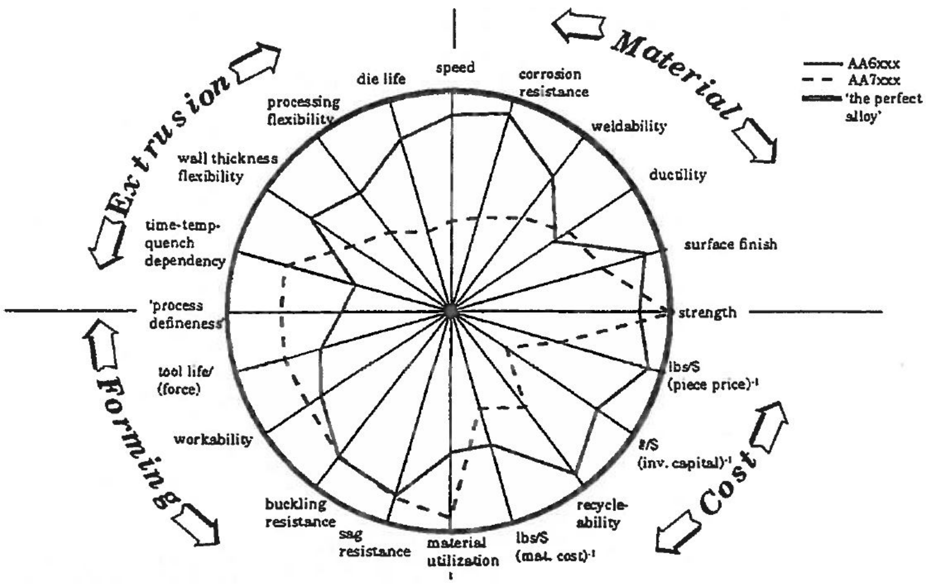

Figure 3.6: Comparison between typical characteristics of AA6xxx and AA7xxx alloys (Welo & Rizk, 1997)

plasticity (Benteler Automotive, 2018).

3.5.2 Pre-heating

The billet is pre-heated, affecting the material properties and enabling more effective flow through the extrusion die. More effective flow increase the efficiency of the process and decrease the press forces required. The press forces required are also affected by geometrical factors of the die and the material choice.

Reducing press forces will reduce friction effects and increase the tool life. The tool life is important not only because of tool cost but also because tolerances will deviate as the tool degrades. The friction effects in the tool are converted into heat, subjecting the billet to a higher temperature towards the end of the extrusion cycle. To compensate for this, the pre-heated temperature is gradually decreasing along the length of the billet.

Throughout the value chain, the rate of heating of the material is a trade-off between process efficiency, the temperature required, and temperature uniformity. The rate of cooling of the material is a trade-off between process efficiency, material properties (material particle size increase with cooling time), and geometrical tolerances (chance of non-uniform cooling shrinkage decrease with cooling time) (Benteler Automotive, 2018). This is illustrated in Fig. 3.8.

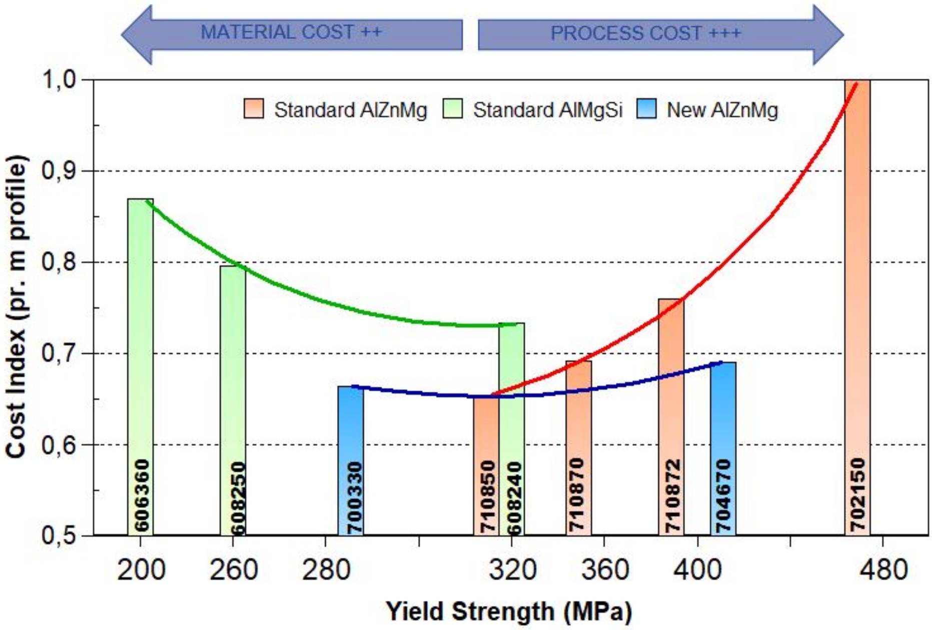

Figure 3.7: Material and process cost related to material choice (Benteler Automotive, 2018).

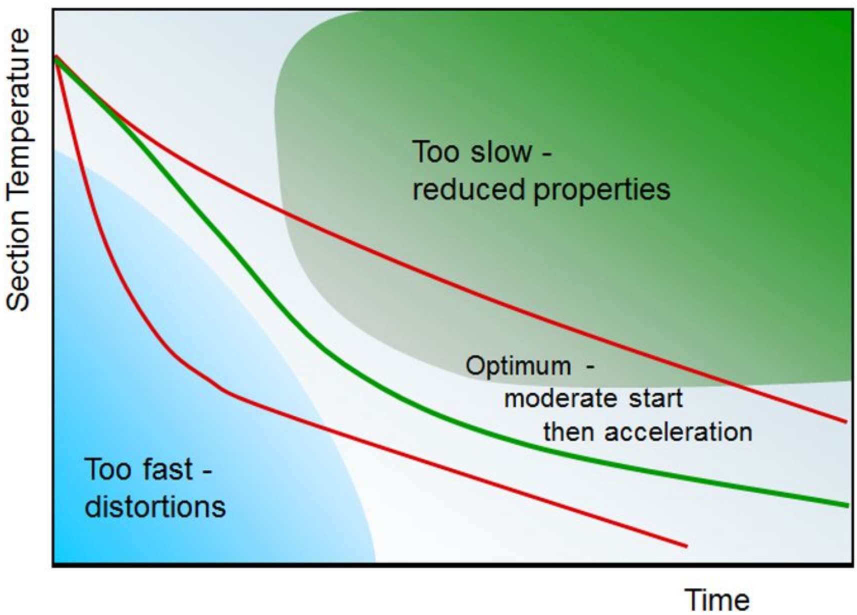

Figure 3.8: Trade-off regarding quenching rate (Benteler Automotive, 2018).

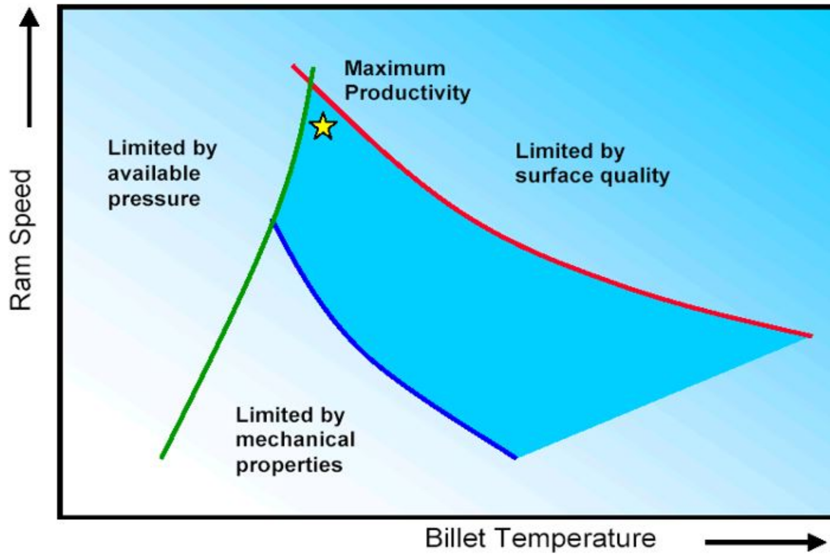

Figure 3.9: Limiting factors in the extrusion process (Benteler Automotive, 2018).

3.5.3 Extrusion

Pressing

Powder is applied to the rear end of the billet. This is to avoid adherence between the billet and the dummy block. The billet is inserted into the container and pressed through the die by the pressing stem. The die is product-specific, providing the cross-section of the extrusion.

There are several trade-offs to consider with regard to ram speed and billet temperature, as illustrated in Fig. 3.9. According to Benteler Automotive (2018), there are several product design considerations regarding the extrusion process:

- For extrusions with one or more closed chambers, the mandrel must be supported by legs splitting the material flow. The material is then welded together by means of temperature and pressure in the welding chamber, exiting the die with one or more closed chambers. The weld (called a "seam weld") will have reduced mechanical properties and reduced aesthetics. Welding poses constraints on the manufacturing process, so the more chambers are in the profile, the less efficient is the process. Generally, friction and temperature are increased with increasing complexity of the profile.

- The die must be designed so that the material flow is evenly distributed so that the extrusion is being pressed out evenly, and to avoid uneven forces wearing the tool. This is an important aspect with regard to tolerances.

- The diameter of the smallest possible circle circumscribing the extrusion's profile is called the circumscribing-circle diameter (CCD). The CCD is an important design aspect, as it must be compatible with the size of the pressing stem and dummy block. This greatly limits the design space of the components.

- The ratio R of the cross-sectional area of the billet and the cross-sectional area of the profile should typically approximately lie between 20 and 60, as higher ratios result in a pressure build-up and subsequent cost increase, while lower ratios result in an ineffective process.

Stretching

As the billet is pressed, the extrusion is pulled across an extrusion table. In this process, the extrusion is stretched to straighten the extrusion and distribute the residual stresses uniformly in the extrusion. This stretching will be as little as possible (typically between $0.3 - 0.5\%$ and maximum 2%), as volume conservation pose dimensional tolerance problems (Benteler Automotive, 2018).

Cutting

At the end of the extrusion cycle of a billet, a new billet is inserted. The extrusion produced by the new billet is pressed onto the rear end of the previous extrusion, welding the two extrusions into one (called a ”charge weld”). The charge weld will have reduced mechanical properties. Additionally, impurities in the material accumulate at the container liner and at the dummy block, in the proximity of the charge weld. Therefore, when extrusions are sectioned, it will be cut in the proximity of the charge weld.

An important design aspect is the cross-sectional area. This will obviously affect the cost and weight of the product related to the amount of material per product. For automotive components, the length of each product is typically pre-determined to a larger extent than the cross-sectional area. A decreased cross-sectional area will increase the length of extrusion (and the number of products) per billet. Additionally, there will be less material is discarded per product (as there are fewer charge welds and areas of impurities per products), reducing the cost per product (Benteler Automotive, 2018).

3.5.4 Cooling

The extrusion is cooled as it is translated across the extrusion table. Uneven cooling may result in uneven deformation and residual stresses in the extrusion. Even cooling is difficult to accurately control, resulting in the tolerance width after the extrusion process to be wide.

3.5.5 Pre-ageing

The extrusions are pre-aged to enhance their mechanical properties. The yield strength at peak ageing is increased by subjecting the extrusions to a lower temperature over a longer period of time, but in order to increase efficiency, the ageing time and temperature are optimised for required yield strength. Additionally, over-ageing generally results in increased ductility compared to under-ageing at equal yield strength (Benteler Automotive, 2018).

Chapter 4

Mapping design space

4.1 Presentation of the 3DBM 2500-A

4.1.1 The 3DBM 2500-A's bending operation

The 3DBM 2500-A consists of two opposing sets of robot arms, each arm constructed as illustrated in Fig. 4.1. Each arm provides three degrees of freedom: a rotational movement along the horizontal direction in the revolute joint (1), a rotational movement along the vertical direction in the revolute joint (2), and a translational movement in the base in the prismatic joint (3) (Paulsen & Welo, 2003). A fourth joint providing a rotational movement in the direction along the extrusion in the revolute joint (4) were considered but never implemented (Røe, 2018). These degrees of freedom will from now be termed pitch (or d.o.f. 1), yaw (or d.o.f. 2), d.o.f. 3 and roll (or d.o.f. 4), respectively.

The extrusion is automatically loaded and unloaded to the machine, clamped at each end by the gripping mechanism of the robot arms, and bent over dies mounted to each of the robot arms (Paulsen & Welo, 2003). The bending operation of the 3DBM 2500-A is a combination of force controlled and strain controlled stretch bending, both illustrated in Fig. 4.2. The d.o.f. 3 provides the tensile pre-stretching of the extrusion characteristic of force controlled stretch bending (Vollertsen, Sprenger, Kraus, & Arnet, 1999). The pitch and yaw provide the die contact characteristics of strain-controlled stretch bending. The two dies mounted at each robot arm represents each half of the final form.

The die contact characteristics of strain controlled stretch bending (and thus the 3DBM 2500-A) compared to force controlled stretch bending are fundamentally different. In strain controlled stretch bending, the interaction between the extrusion and die involves much less friction as there is (theoretically) no relative movement at each point of contact once contact is established.

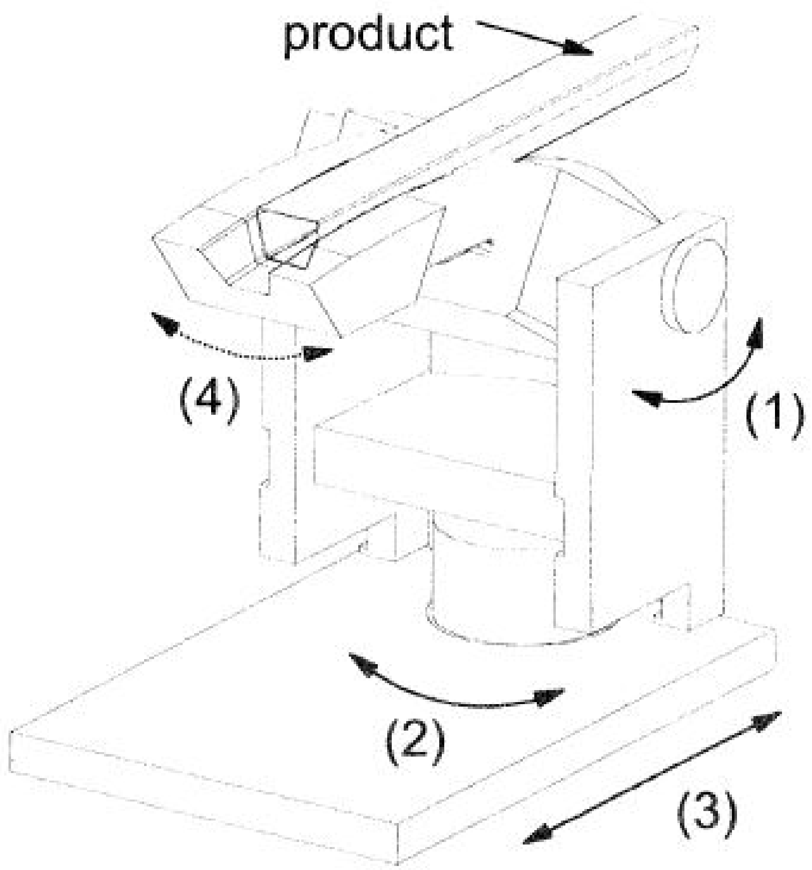

Figure 4.1: An illustration of one half of the 3DBM 2500-A (Welo & Holte, 2006).

4.1.2 The 3DBM 2500-A's machine elements

The d.o.f. 1 and d.o.f. 2

The joints of the d.o.f. 1 and d.o.f. 2 provides the horizontal and vertical pivot point, respectively, accommodating bending in three dimensions. Each die is provided a turning moment around the pivot points, continuously stretching the extrusion to a fixed final strain (Vollertsen et al., 1999).

The position of the pivot points is critical. If the pivot points are positioned such that the length of the workpiece is not strictly increasing during the bending stroke, the workpiece will experience a relaxation resulting in a large degree of springback, as illustrated in Fig. 4.3. Beside mechanical considerations during tooling construction, the pivot points can be adjusted horizontally with the d.o.f. 3 (Røe, 2018; Welo, 2018).

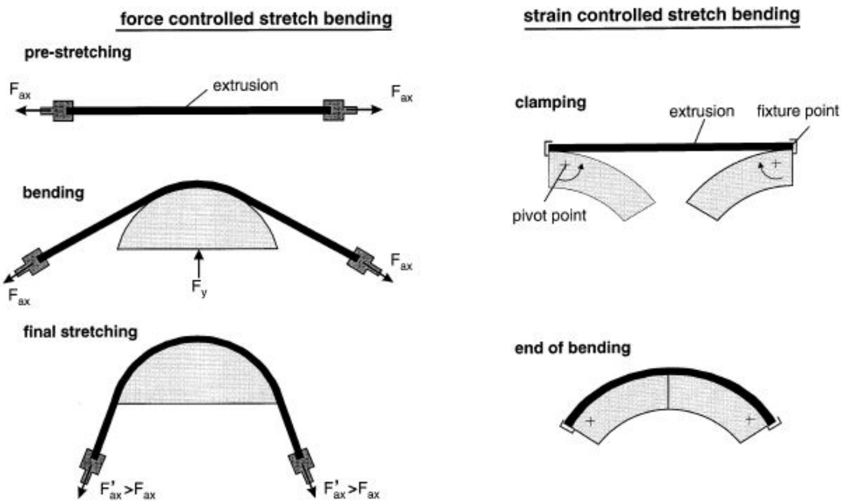

Figure 4.2: Force controlled and strain controlled stretch bending (Vollertsen et al., 1999).

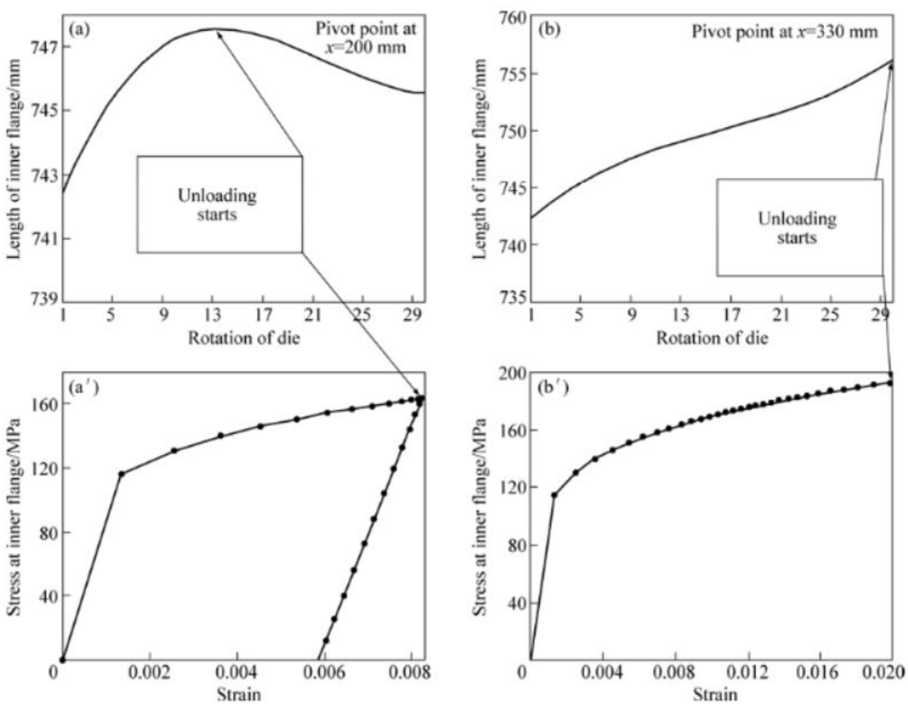

Figure 4.3: To the left: Inadequately positioned pivot points resulting in a large degree of spring-back. To the right: Adequately positioned pivot points (Welo & Widerøe, 2010).

The d.o.f. 3

The translational movement of the d.o.f. 3 provides several advantages. Firstly, the machine can accommodate extrusions of different lengths, supporting the flexibility of various products needed in mass customisation (Chandra & Kamrani, 2004). Secondly, it enhances the machine's repeatability (Paulsen & Welo, 2003), supporting the effectiveness needed in mass customisation (Chandra & Kamrani, 2004). Lastly, it can adjust the tension during bending.

The d.o.f. 4

If the torsional movement of the d.o.f. 4 was implemented, the machine could to a certain degree introduce torsion in order to accommodate twisted geometries, as well as introduce counteracting torsion to eliminate unintended twists (Vollertsen et al., 1999). This gain was deemed insufficient compared to the economic cost of implementing this joint (Røe, 2018).

The tools

Each set of tools consists essentially of a die and a gripper, as presented in Fig. 4.4. The tools are product-specific, which reduces flexibility of the process. Because of this, each tool is constructed as one solid component in order to provide a rapid detachment and attachment process for tool change of between 10 and 20 minutes (Paulsen & Welo, 2003; Røe, 2018).

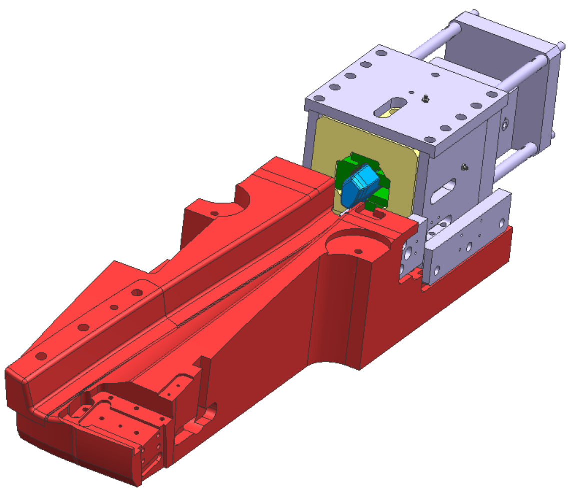

Figure 4.4: A CAD model of the die (red), clamps (green), mandrel (blue), housing (yellow) and translation system (purple)

The dies in this bending operation are the overall shape-defining factors. This is fairly rigid compared to kinematic bending operations without dies, where the shape-defining factor is the relative motion of the position of the clamped extrusion ends (Vollertsen et al., 1999). The production process of the tools for each new bending geometry and the transition time during die change reduces the flexibility, but the dies' rigidity can enhance the machine's reproducibility and decrease lead-time (Vollertsen et al., 1999), as is necessary for mass production processes.

The gripper, as illustrated in Fig. 4.5, consists of three interacting parts: housing, clamps and mandrel. The housing encloses the clamp, mandrel and the extrusion end to be clamped. The clamps have friction patterns facing the extrusion. The housing and clamps interact in an angle relative to the extrusion. Because of this, relative movement (longitudinally with the extrusion) between the housing and the clamps forces the friction pattern of the clamps into the extrusion. The angle provides a high mechanical advantage, so the pressure applied to achieve the relative movement is small relative to the obtained pressure of the clamps. The mandrel supports the interior of the extrusion against the pressure of the clamps.

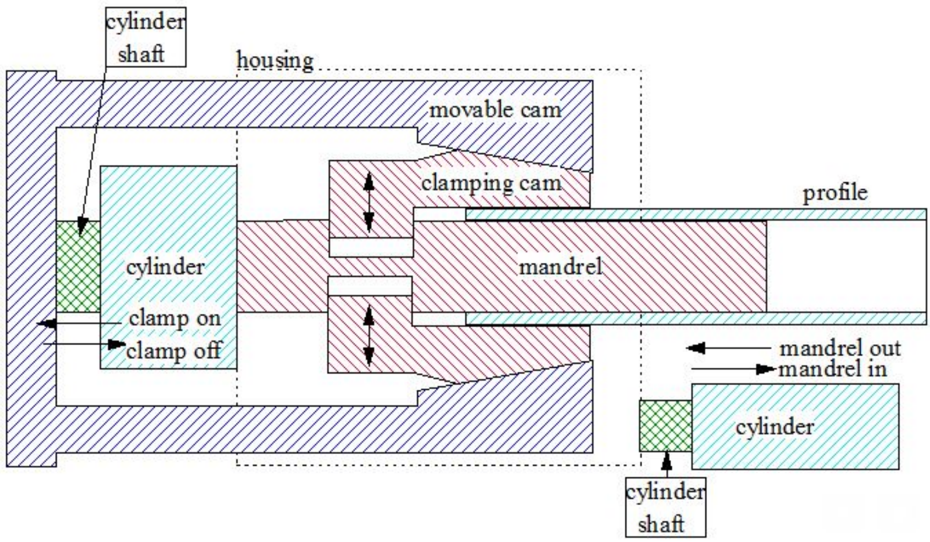

Figure 4.5: Cross-sectional cut of the 3DBM 2500-A's gripper

The gripper is constructed according to the principle of the Chinese finger trap. When the product is pulled, the clamping is pulled accordingly due to the obtained friction between clamping and the product. The clamps wedges between the housing and the product. The wedging results in normal forces and the product will be fixed if the increased friction forces exceed the pulling forces. Additionally, the friction pattern will penetrate the product further, increasing the friction area and thus the friction force (Røe, 2018).

The workpiece

The workpieces to be bent are extrusions of aluminum alloys, most prominently of the types 6082 T5/T6, 6005 T5/T6, 6063 T5/T6 (and possibly 6060 T5/T6). The material data of these alloys was obtained by the customer and are listed in Table 4.1, with plastic behaviour as indicated in the stress-strain curves in Fig. 4.6. For terminology used in this paper of the profile features, please refer to Appendix C.

Alloy	ρ [$Tonnes/mm^3$]	E [Mpa]	μ	σ_y [MPa]
H13 Steel	7.8e-9	215 000	0.3	1000 - 1380
6082 T5/T6	2.72e-9	70 000	0.3	261
6005 T5/T6	2.72e-9	70 000	0.3	238
6063 T5/T6	2.72e-9	70 000	0.3	190.1
6060 T5/T6	2.72e-9	70 000	0.3	176.4

Table 4.1: Material data (AZoM, 2013; Paulsen, 2018b)

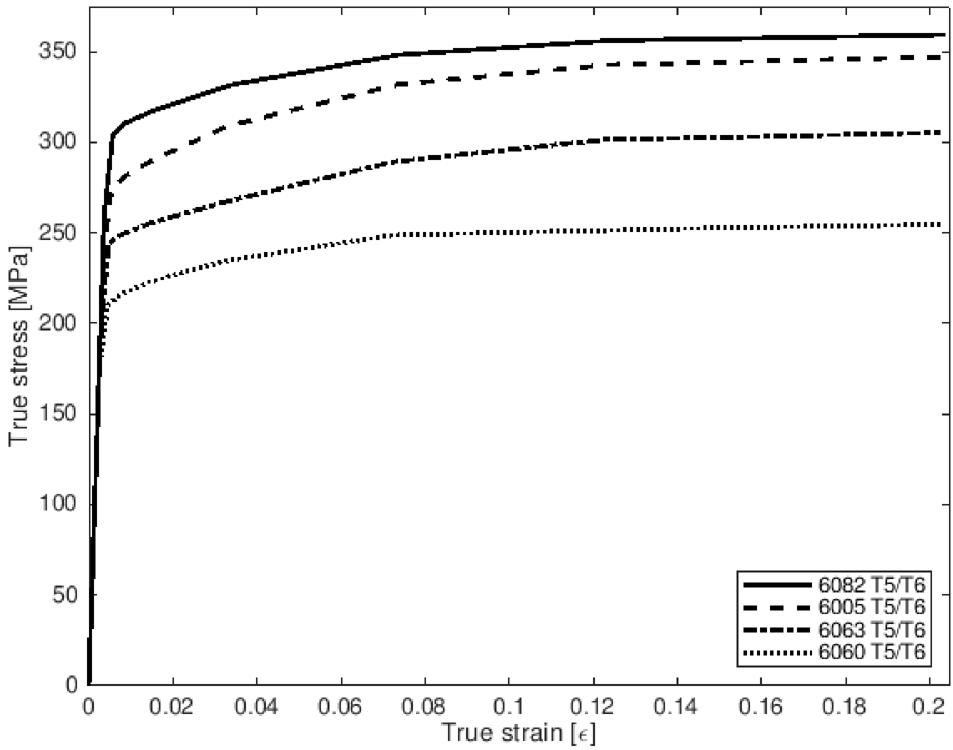

Figure 4.6: True stress-strain curve of the aluminum alloys (Paulsen, 2018b)

4.2 Literature study of parameters influencing bending

4.2.1 Aim of literature study

The aim of the literature study of parameters involved in the bending operation is to present some of the parameters influencing the deformations. Not all will be covered, and the extent of the influence will not be evaluated. The rationale for performing this literature study is because it is essential to study these deformations in order to understand what considerations are important when constructing the bending machine, and how to engineer the extrusions to behave as intended.

The deformation of the workpiece will be classified into intended and unintended deformations. The intended deformation will be defined as the desired, final geometry of the product obtained by the bending operation, and the actual deformation will be defined as the deformation of the workpiece at its current state. The deviation between actual and desired deformation will be defined as unintended deformation. The unintended deformations can be classified as formability, cross-sectional distortions and overall dimensional tolerances of the extrusions (Paulsen & Welo, 2003; Yang et al., 2012), as illustrated in Fig. 4.7. The literature study of parameters involved in the bending operation will be classified into operational, material, and geometrical parameters.

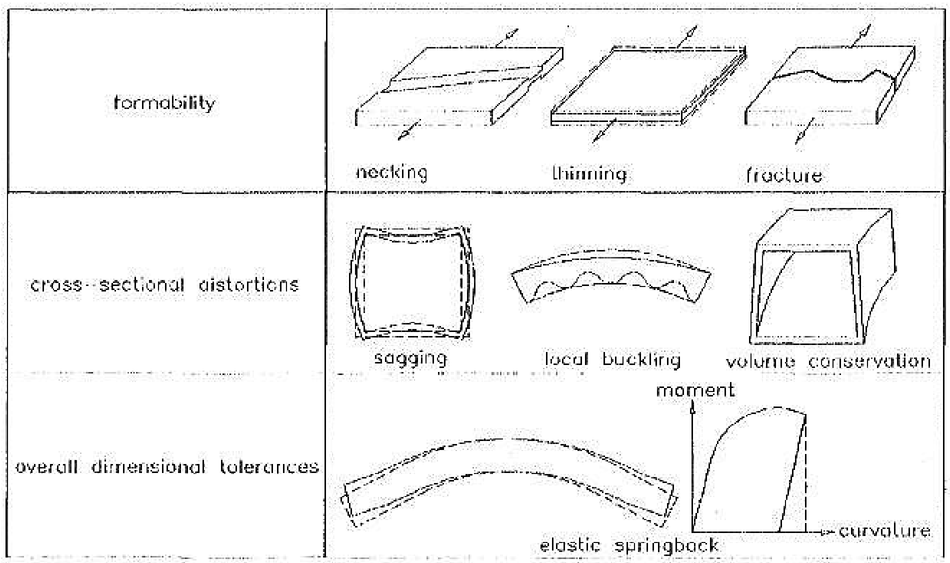

Figure 4.7: Common problems in bending processes (Welo & Paulsen, 2001).

- Operational parameters will be defined as parameters regarding the bending operation related to the bending machine. As flexible, three-dimensional stretch bending is a novel bending technique, limited academic research is available. In the aim of increasing the literature study's applicability, the literature study is mainly focused on force and strain controlled stretch bending techniques (of which the bending operation of the 3DBM 2500-A is a hybrid), if not stated otherwise. Parameters reported in the sources to affect bending deformations in a general sense will be included as well.

  The specimen's parameters are affected by the processes it has been subjected to along the work stream. As this varies among the various sources, the literature study's applicability may be affected. In order to address this failure mode, the sources investigated will be peer-reviewed, academic papers from well-established journals, increasing the sources' reliability with regard to control of influencing parameters.

- Material parameters will be defined as workpiece-related material parameters. The literature study will not solely concern aluminum. The rationale for this is that the parameters reported to influence other materials will in most cases influence aluminum to a certain degree as well. This may cause disproportionate attention to certain (potentially negligible) parameters.
- Geometrical parameters will be defined as workpiece-related geometrical parameters. Firstly, there are geometrical parameters due to engineering decisions. These parameters are directly controllable, and thus important to establish so engineers can minimise the geometry's proneness to unintended deformations. Secondly, there are tolerance variations.

4.2.2 Parameters influencing formability

Necking, thinning and cracking are all typical unintended deformations regarding formability. The driving factor of these deformations is subjecting the specimen to localised stress beyond the material's ultimate strength. These responses are analogue to deformations under pure tensile stress, though more complex due to the unevenness of the stress across the cross-section.

- Operational parameters
  - The bending method used can influence the tendency of necking or fracture. For example, stretch or press bending increase the possibility of these modes of deformation (Welo, 1996).
- Material parameters
  - All material parameters affecting the relationship of stress and strain up until the material's ultimate strength can influence the possibility of localised stress reaching this limit.
  - The material properties most important to the specimen's formability is strain hardening, strain rate sensitivity and anisotropy (Welo, 1996).
- Geometrical parameters
  - The cross-sectional geometry affect the distribution of stress which may cause localised stress beyond the material's ultimate strength (Welo, 1996).

4.2.3 Parameters influencing cross-sectional distortions

Sagging, local buckling and volume conservation are all typical unintended deformations regarding cross-sectional distortions. The driving factor of local buckling, often termed wrinkling, are due compressive stress in the intrados, influencing the structure to align to a lower energy path.

Cross-sectional distortions affect the aesthetics, service capabilities and tolerances in regions to be joined to other parts (Welo, 1996). Local buckling, especially of operations regarding large diameter tubes bent over a small bending radius, is one of the major bottlenecks for improving bending limit and tolerances. The product's strength, stiffness and fatigue life are reduced, as well as the forming limit and the overall bending quality. These deformations can also cause complications on a larger process scale, such as tool wear and damage, and process interrupts (Yang et al., 2012).

- Operational parameters
  - Mandrels supporting the inside of the cross-section can reduce cross-sectional distortions (Welo, 1996). The mandrel parameters are then obviously of importance. The possibility of local buckling increases with the clearance of the mandrel and the extrusion and decreases with the friction between the mandrel and the extrusion (He, Jing, Mei, Heng, & Yongle, 2009).
  - Loading conditions and especially contact conditions are the key factors for local buckling (Yang et al., 2012). The possibility of local buckling during a rotary draw bending operation decreases with increasing friction between dies and workpiece and decreases with the clearance between tube and tooling (He et al., 2009).
  - Applying tensile stress can reduce local buckling, but can increase the other forms of cross-sectional distortions. Applying internal pressure can reduce all the forms of cross-sectional distortions, acting as a fluid mandrel. Combining tensile stress and internal pressure provides further benefits in terms of cross-sectional tolerances (Wang & Agarwal, 2005). It should be noted that, for aluminum alloys under small bending radii, hoop strain is not negligible and may result in thinning or flattening (Yang et al., 2012).
- Material parameters
  - Plastic anisotropy and strain hardening are reported to be major influences of cross-sectional distortions (Paulsen & Welo, 2001).
- Geometrical parameters
  - The width-to-thickness ratio is the main parameter for buckling in the inelastic range (Paulsen & Welo, 2001).
  - The possibility of local buckling increases with larger tube diameters (Yang et al., 2012).

4.2.4 Parameters influencing overall dimensional tolerances

Springback is the elastic response after unloading a workpiece bent to plastic deformation. It affects the curvature of the bent extrusion, as illustrated in Fig. 4.7.

Springback is one of the major bottlenecks with regard to bending quality and process. It increases the die and product costs, as well as decreasing the efficiency of the process (Yang et al., 2012). Springback is dependant on a large variety of parameters with complicated inter-dependencies (Vollertsen et al., 1999). It is to a certain degree present in all bending operations but is reversible in the sense that over-bending can compensate for the unintended deformation. Prediction based on experimental results are reliable but limited to the conditions of the experiments (Yang et al., 2012).

In industry today, springback is predicted analytically and determined experimentally, and the bending operation is adjusted to compensate for the springback. Thus, springback in itself is not a big factor; the reason for constructing tools to reduce springback, is that the more springback you have, the more sensitive the springback of the workpiece is to variations (Paulsen, 2018c).

- Operational parameters
  - Applying tensile stress can reduce springback (Paulsen & Welo, 2003). The axial force during the pre-stretching in a force controlled stretch bending should typically not exceed 10% beyond yield point but should be increased during the bending, typically not exceeding 100% beyond the yield point (Vollertsen et al., 1999).
  - Tribology of the dies can affect springback (Vollertsen et al., 1999).
  - Temperature variations affect workpiece and die temperatures, which can influence the bending result (Schaller, Raggenbass, & Reissner, 1995; Vollertsen et al., 1999).
  - For hydraulic systems, heating of the hydraulic oil through internal friction or environment parameters may affect machine control (Schaller et al., 1995).
- Material parameters
  - Young's modulus, 0.2% offset yield strength, thermal treatment, and strain hardening are all reported to affect springback in bending operations in general (Vollertsen et al., 1999).
  - Anisotropy is one of the major factors influencing springback (Vollertsen et al., 1999).
  - Residual stress of the workpiece (Vollertsen et al., 1999). Residual stress can be preventatively reduced through heat treatment prior to the bending operation.
  - Tribology of the workpiece may influence springback (Schaller et al., 1995), but as the 3DBM is strain controlled, it is less dependent on friction compared to most bending operations (Paulsen, 2018c).
  - Increased Young's modulus and hardenability decrease springback, while increased yield stress and strength factor increase springback (according to an FEM analysis of rotary draw bending) (Gu, Yang, Zhan, & Li, 2006). A similar analysis of titanium alloys adds that springback decreases with increasing hardening exponent and the thickness anisotropy exponent, and increases with

increasing hardening coefficient. Further, springback increases with increasing bending angle, as does the influence of all the reported parameters. The Poisson ratio is of negligible influence (Jiang, Yang, Zhan, Xu, & Li, 2010).

  - Time-dependency is an issue for certain materials, aluminum especially, after rotary draw bending (Wang, Wagoner, Carden, Matlock, & Barlat, 2004). The response may continue between one minute to 15 months after the bending process, reaching near-saturation after a couple of months, and may constitute up to 20% of the total springback (Wang et al., 2004). The time-dependency is believed to be due residual stress driven creep, though anelasticity may be of influence in the short-term response (Lim, Lee, Sung, Kim, & Wagoner, 2012; Wang et al., 2004).
  - Steady forming is a state where a linear relationship between the springback angle and the bending angle is established. In rotary draw bending, prior to this state, this relationship is nonlinear. The amount of time before steady forming is established increases with decreasing bending radius and tube diameter. The nonlinearities of the unsteady state are less distinct for aluminum alloys than for stainless steels, and steady forming are established faster (Gu et al., 2006).

- Geometrical parameters
  - Cross-sectional geometry affect the stress distribution, and thus springback. The width-to-thickness is one of the main influences along with the second moment of inertia (Vollertsen et al., 1999).

4.3 The 3DBM's gripping mechanism

4.3.1 Breakdown into sub-systems

A gripping mechanism is a sub-system of the 3DBM, which can be further classified into the sub-systems:

- Mandrel, in this context defined as any part of the gripper in contact with the interior of the extrusion cross-section.
- Clamp, in this context defined as any part of the gripper in contact with the exterior of the extrusion cross-section.
- Friction surface, in this context defined as any part of the gripper meant to provide friction against the workpiece.
- Housing, in this context defined as any part of the gripper enclosing the mandrel and clamp.

This breakdown is based on the gripping mechanism of the 3DBM 2500-A, and are developed with the aim of aiding concept set development and communication. This classification may be altered throughout the development process, as sub-systems may be added, removed or otherwise altered beyond its definition as the project evolves. The gripper interacts with various other sub-systems of the 3DBM, most notably the workpiece and the rest of the tool.

4.3.2 Decide on level of innovation to sub-systems

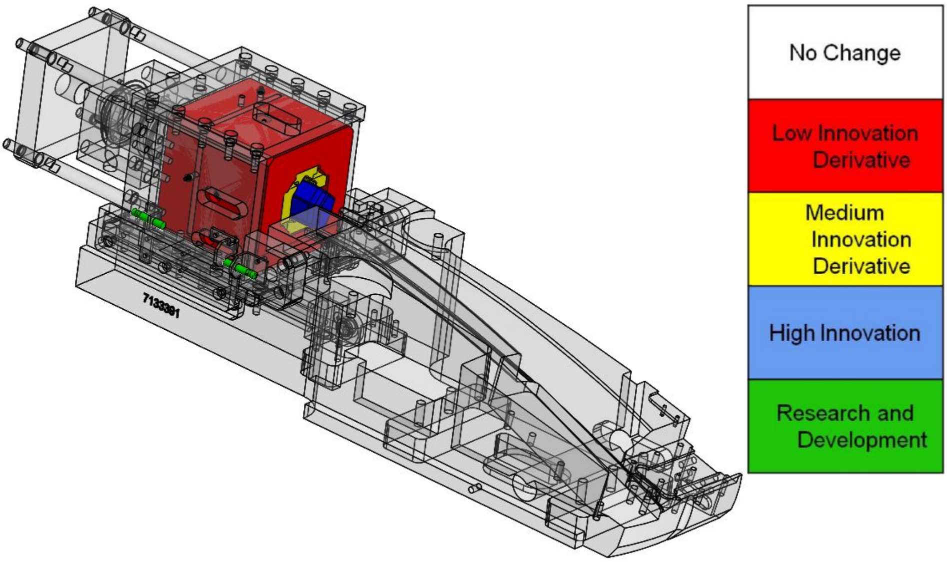

Figure 4.8: Degree of innovation in project

4.3.3 Defining feasibility regions

The feasibility regions are defined based on information gained through interviews of employees and documentation at the automotive parts manufacturer. The feasibility regions are communicated in bounded intervals and presented in Table 4.2.

Category	**Feature**	**Value**	**Unit**
Extrusion geometry	Cross-sectional area	≤ 1200	mm^2
	Extrusion height	≤ 100	mm
	Extrusion width	≤ 100	mm
	Wall thickness	$\geq 1.6, \leq 7$	mm
	Min wall thickness	≥ 1.8	mm
	Mid wall distance to wall	≥ 10	mm
	Inner radius	≥ 0.5	mm
	Outer radius	≥ 0.5	mm
	Flange radius	≥ 0.5	mm
	Grip length	≤ 40	mm
Housing geometry	External height	≤ 210	mm
	External width	≤ 210	mm
	External depth	≤ 210	mm
	Housing floor to die floor	90	mm
Standard tolerances	Beam end profile surface tolerance	± 3	mm
	Beam general surface tolerance	± 2.5	mm
	Beam trim end surface tolerance	± 2	mm
	Extrusion thickness, external wall	± 0.3	mm
	Extrusion thickness, internal wall	$-1.0/+0.5$	mm
	Extrusion profile dimensions	± 1.5	mm
	Gap between extrusion legs, open profile	± 15	mm
Cycle time	Workpiece loading time	≤ 3	s
	Fixation time	≤ 3	s
	Workpiece unloading time	≤ 3	s
Forces	Force, every axis	≤ 200	kN
	Fixation tensile force	≥ 200	kN
Movement speed	Speed, vertical bending at 200kN	≤ 60	$\frac{mm}{s}$
	Speed, horizontal bending at 200kN	≤ 50	$\frac{mm}{s}$
	Speed, translation at 200kN	≤ 20	$\frac{mm}{s}$

Table 4.2: Feasibility regions (Benteler Automotive, 2002, 2018; Paulsen, 2018a)

Chapter 5

Concept set development

5.1 Tools

5.1.1 Integrate models

The process of employing computer tools in the development of the gripping mechanism is illustrated in Fig. 5.1.

CAD models of the 3DBM 2500-A were obtained from the customer. This was essential in order to integrate novel solutions to the existing die geometry of the 3DBM 2500-A. These were either ”STEP” files or files from the CAE software Siemens NX. The files from Siemens NX were evaluated in its original software before exported as ”STEP” files. The ”STEP” files were imported into the CAD software Solidworks. Solidworks was chosen as CAD software because it offers the functionalities:

- Continuous modelling functionality, where design features may be manipulated with automatic update of all related features.
- Flexible assembly functionality, where ease of use accommodates modular system design.
- Feature recognition capabilities, where foreign CAD models are analysed and automatically remodelled with explicit design parameters.
- 3D printer compatibility.

The ”STEP” files were analysed by the feature recognition capabilities to acquire explicit design features of the model. The systems were assembled with novel components integrated to check for their interaction, and both the original components and the novel components were remodelled, in assembly, with the continuous modelling functionality to optimise the global design with various interacting design parameters. The continuous modelling functionality accommodated a set-based approach to the design features, as parameters were easily altered.

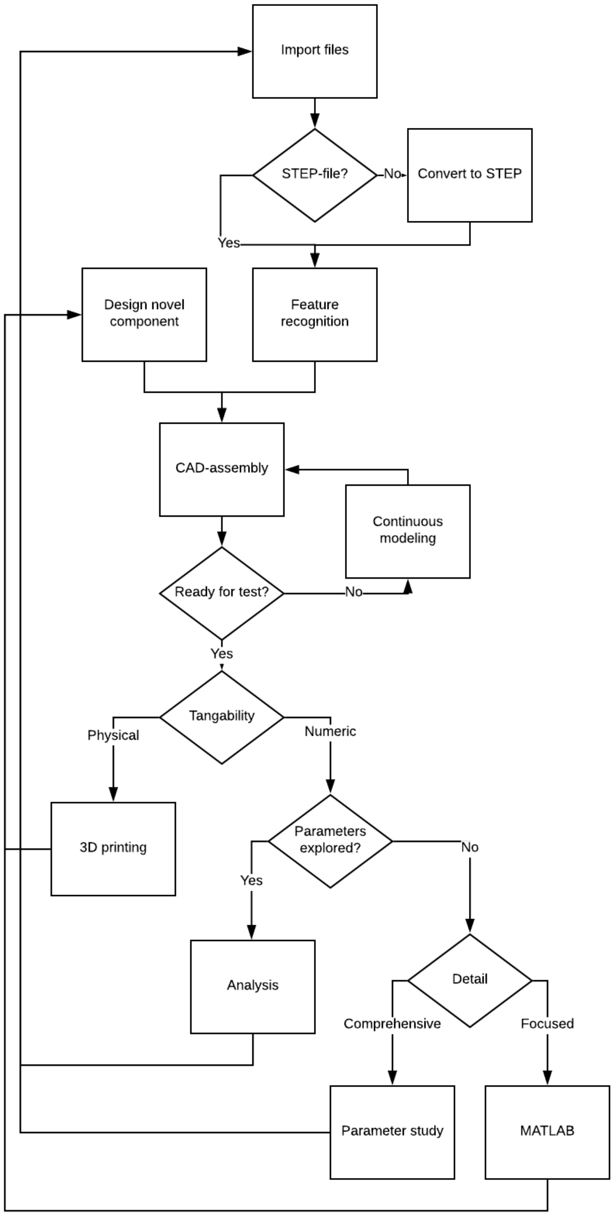

Figure 5.1: Design iteration cycle

In addition to the CAD models of the 3DBM 2500-A, models of relevant profiles were obtained from the customer. A header frame was evaluated to pose the most constraints on the design space, which was necessary in order to address all eventualities. The header frame is presented in Fig. 5.2. The rest of the obtained models are presented in Appendix B. The header frame was chosen as a test profile because it contained the features:

- Chambers with a mid-wall.
- The most narrow internal surfaces of the available models.
- Complex chamber geometry and walls with angles.
- A large flange and two smaller, over-hanging flanges.
- A geometry intended for a three-dimensional stretch bending operation.

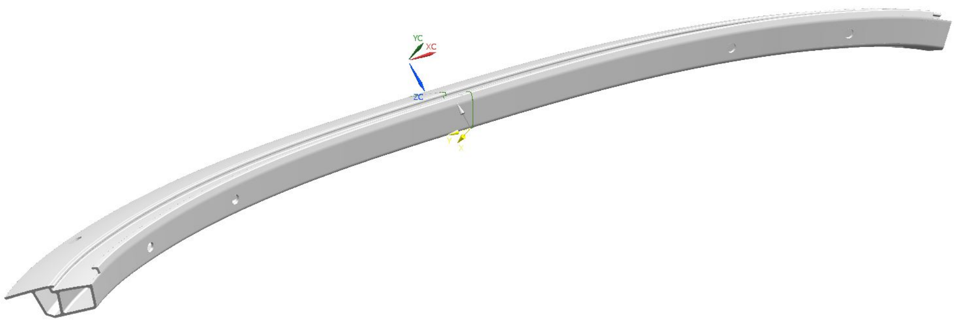

Figure 5.2: The test profile (a header frame)

5.1.2 Parameter studies

Fundamental design features were rapidly analysed with the numerical computing software MATLAB. Parameter studies in MATLAB were performed by abstracting concepts to establish mathematical relationships with design parameters and performance outcomes, and either looping the calculations with the design parameters as variables or constructing the design parameters as a mesh grid over which the performance outcome plots a surface.

Time-consuming parameter studies based on FEM analyses were conducted with the CAE software Abaqus. Abaqus was chosen as CAE software because it offers the functionalities:

- Accurate material plasticity simulation.
- Accurate contact simulation.
- Scripting compatibility.

The scripting compatibility accommodated scripts in the programming language Python to perform repetitive tasks (such as creating a material model) and parameter studies. Familiarity with Abaqus' journal files was obtained by gradually constructing CAE models to investigate how changes were recorded in the journal files.

The scripts for automating repetitive tasks were constructed by doing the task to be automated and extracting the relevant code from the journal file. The parameter studies were constructed by fully constructing the CAE models to be investigated, and then utilise Abaqus' "Macro Manager" to record changing the parameters to be studied. Both of these processes could be performed by either procedure. The recorded changes are extracted and copied into a Python-script.

Parameter studies in Abaqus are performed by converting relevant parameters into variables in loops. The loops contain code to submit the job and extract the desired data to a separate worksheet ("Microsoft Excel" was chosen). For extracting the data, it is important to ensure that everything except the variable design parameters is constant throughout all analyses. This implies that for geometrical parameter studies, the model and assembly must be constrained thoroughly. Further, as the models must be regenerated and re-meshed (deleting node and element sets) for each iteration, a geometry set must be investigated.

In order to avoid complications due to idle time in the user interface, the jobs were submitted through the command-line interface Windows Powershell and monitored through Abaqus' status and message files.

Models from Abaqus with design parameters as desired were exported as "STEP" files, to be analysed by the feature recognition capabilities in SolidWorks once again. This iterating loop ran throughout the project. When fit, the CAD models in Solidworks were exported as "STL" files, and imported in the 3D printing pre-processor software Cura, and printed in PLA plastic by the 3D printers "Prusa i3 MK3", to evaluate physical prototypes.

5.1.3 Analyses

When fit, analyses in CAE analyses were conducted. The CAE models were gradually constructed with an increasing degree of complexity. This is an iterative process, where the results of each analysis are evaluated. Each model is developed through two iteration loops: the first one aims to converge at a solution which accurately represents the conditions of the real world problem (model and boundary conditions), the second one aims to converge at a solution which accurately represents the detail of the real world problem (mesh and solver). It should be noted that the second iteration simply converges to the solution of the problem modelled in the first iteration.

CAE analyses were actively employed during the development process of each subsystem. If the results of the second iteration loop were evaluated to be unacceptable, the relevant components were redesigned or discarded. This gradual refinement ensured fewer iteration loops during the integration of all sub-systems, as all sub-systems were correctly defined and structurally sufficient. Sets of all relevant surfaces were defined according to an established naming convention in order to accommodate debugging.

In order to reduce modelling and processing time, the initial models had very coarse, automatically assigned tetrahedral mesh. Additionally, the analyses were performed with static solvers, preferably with displacement-controlled loading conditions in order to easier ensure convergence. Interaction was simply modelled as boundary conditions with constrained d.o.f. As the necessity of detail grew, the models were defined in a more accurate, detailed manner.

5.2 Sub-system set generation

5.2.1 Extracted design concepts

System

Interviewee C (interview A.11) stated that some of the most important factors when designing a good gripping mechanism is

- ”(...) that it is a safe process”
- ”(...) that there is as little maintenance as possible”
- ”(...) that you can grip hard enough”
- ”(...) what angle you are clamping with”
- ”(...) complexity in the entire unit with regard to assembly, disassembly, maintenance, and the like”

Further, interviewee C added that ”There is a contradiction: if it is going to be flexible, then it becomes very complicated”, and that his experience was that ”(...) you won’t find a solution which fits everything”. The joints and transmission of forces in the housing (and the gripping mechanism in general) must be extremely robust. Generally, there should be as few joints as possible, mostly sliding movement, and mechanical contact or gas springs for returning movement.

Interviewees C and B (interview A.11 and A.12) explained that they employ ”T-track” joints for translatory movement with return action, circular bolts as a hinge joint for rotary movement in two dimensions, and the ”dog bone” joint for rotary movement in three dimensions.

The system must be easily maintainable, with all parts easily detachable. Further, friction in joints should be kept to a minimum. This is mainly addressed by lubrication and material choice (a bronze alloy with graphite particles for the 2DBM).

The 2DBM and the 3DBM 2500-A are mainly propulsed by hydraulic pistons. Interviewee B (interview A.2) stated that hydraulics may be a bit slow, but ”(...) you can make it pretty compact and still get a lot of force”, and that ”(...) when the pressure is on – if something happens so the system yields – it will apply more force all the time”.

Interviewee A (interview A.14) stated ”(...) if we’re only going to make five products [we use] (...) A die of wood instead of steel [as it] (...) costs next to nothing – five to ten thousand NOK”.

Clamping

The design of the 3DBM 2500-A is explained in Section 4.1, and is proven to work The 2DBM can generally be viewed as a 3DBM with only two dimensions to manipulate. The 2DBM have certain similarities to that of the 3DBM 2500-A, but it has a different gripping mechanism, as illustrated in Fig. 5.3.

The 3DBM 2500-A accommodates clamping from all angles with a translation decline of 5°, providing a force amplification factor of 11.43. The 2DBM solely accommodates clamping from above counteracted by the die with a translation decline of 7°, providing a force amplification factor of 8.14. The 2DBM relies on constant force application (no self-locking mechanism). Interviewee B (interview A.2) stated that with the 2DBM "(...) you have to keep on applying force. If anything happens so that anything fails, you have to apply force straight away. But, this one is faster, because you grip in one motion – translating it in, and grip simultaneously as you are translating".

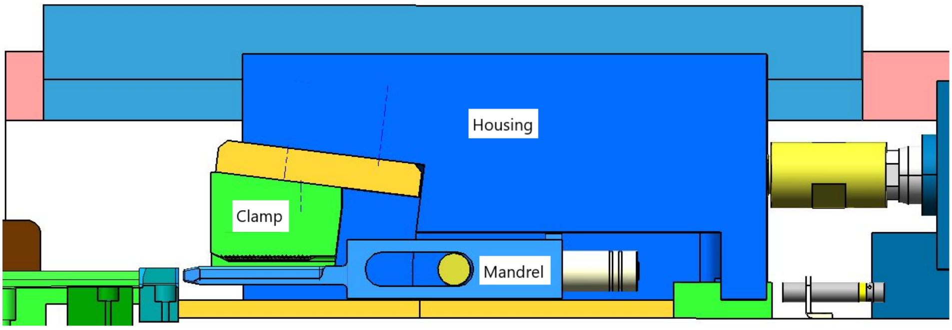

Figure 5.3: Cross-sectional cut of the 2DBM's gripper

Interviewee A (interview A.8) stated that "(...) gripping may be positioned on the profile, or on the machine"; the R&D workshop at the automotive parts manufacturer – for extremely small batches – "(...) weld two brackets onto it (the workpiece), with holes that you may insert a bolt through", which is subsequently cut. "You can't get anything cheaper than that – at least if you are going to make only five products".

Mandrels

The mandrels' function is to provide support inside the cross-section to avoid cross-sectional deformation. The cross-sectional deformations may be caused by clamping or excessive bending. The automotive parts manufacturer is currently using product-specific mandrels to counteract the clamping forces. Interviewee C (interview A.11) stated "You have to have an individual mandrel. Anyways. You can't have a mandrel which adjusts in size".

Interviewee D (interview A.10) stated that mandrels to support cross-sectional deformation due to excessive bending throughout the entire cross-section is desirable, but often not feasible due to complications during extraction. To avoid cross-sectional deformation in excessive bending close to the gripping surface, the automotive parts manufacturer typically extends the mandrel to support the bend, where the curvature of the mandrel's tip equals the curvature of the bend it is to support. This solution necessitates product specific mandrels. According to interviewee B (interview A.4), the R&D workshop at the automotive parts manufacturer has experimented with element mandrels as well as balloon mandrels. Interviewee D (interview A.10) stated that plastic mandrels are often utilised as additional support in bending of aluminum, for example as support for overhanging flanges.

Friction pattern designs

Interviewee A (interview A.5) stated that ”there is actually no direct guidelines” when deciding friction patterns, and that it is traditionally mostly based on experience. Further, the interviewee stated that a general rule is to use a pyramid pattern for aluminum AA6xxx alloys and a line pattern for aluminum AA7xxx alloys – ”but, if you have problems, you may try something different in order to make it stick”. A rough friction pattern is another pattern which might be used at the automotive parts manufacturer. Interviewee A stated that ”sometimes that works as well. It depends on how much force you need for the stretching”.

A CAD model of the pyramid and line friction pattern was obtained. The patterns are presented in Fig. 5.4. The patterns were analysed with the feature recognition feature in order to measure the geometry. It was revealed that one pyramid has a quadratic base area of $6.25mm$, a surface area of $7.12mm$, and therefore an area scaling factor of $\frac{7.12mm}{6.25mm} = 1.1392$, while one line has a base area of $3.275mm$ per length, a surface area of $3.687mm$ per length, and therefore an area scaling factor of $\frac{3.687mm}{3.275mm} = 1.1258$. The patterns are produced by milling in a grid or a line, respectively, and its constituent parameters may be manipulated by the choice of mill tool and pattern density.

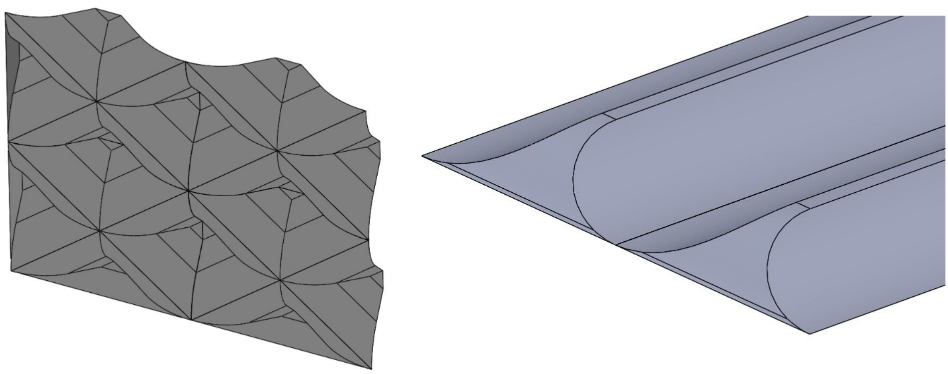

Figure 5.4: CAD models of the pyramid (left) and line (right) friction pattern

The friction patterns are typically milled into separate blocks which are fastened to the clamps but sometimes milled directly on the clamps as well. The reason for separating them is that the friction patterns are prone to wear. Additionally, there is a requirement from the automotive companies that every product is marked for subsequent identification. If this marking is unreadable, the automotive company will not accept the product. In the 2DBM, this marking is performed during the gripping operation, as a part of the friction pattern. Interview A stated that this was a bad solution, as small slippage may destroy the product.

5.2.2 Presentation of sub-system sets

The concept set generation resulted in clamp and mandrel concepts as illustrated in the concept classification trees in Fig. 5.5 and 5.6, with combinations of clamp, mandrel and friction pattern as structured in the concept combination table in Table. 5.1.

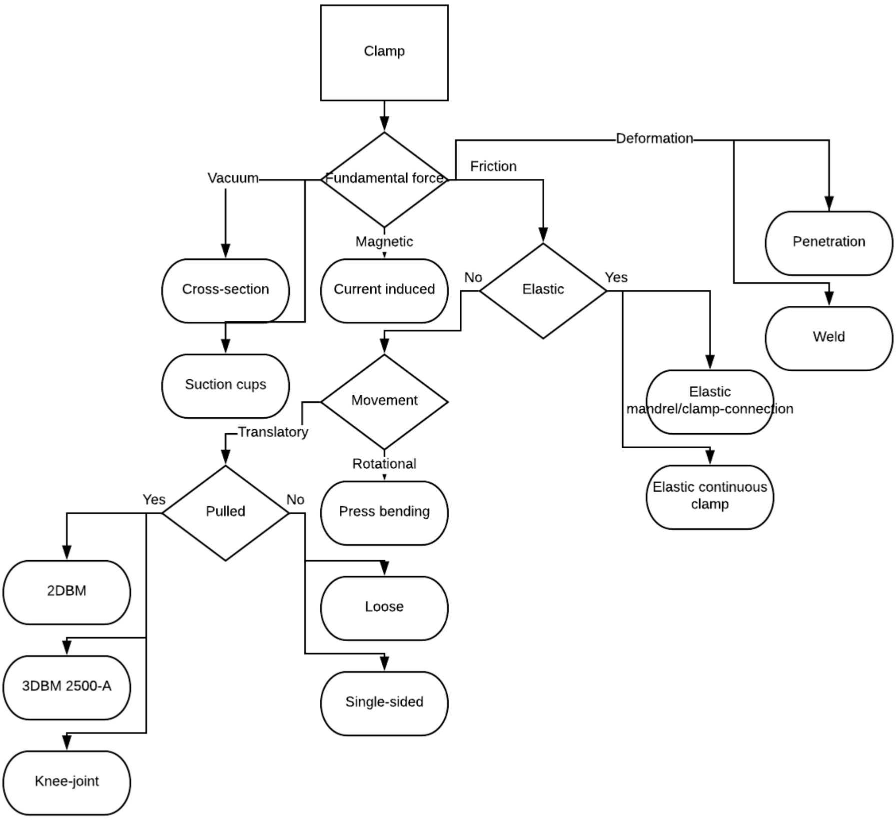

Figure 5.5: Concept chart for clamps

While some sub-systems can or must be combined, other can or must be implemented independently. An example of this is the clamp concepts relying on friction: most of these concepts must be combined with a mandrel concept for support in order to avoid excessive deformation, while the crush clamp concept relies on excessive deformation and can therefore not be combined with a mandrel concept. Adding the various concepts and their possible combinations indicate that

$$5 + 8 \times 7 \times 5 \times 3 = 845 \tag{5.1}$$

unique concepts were generated.

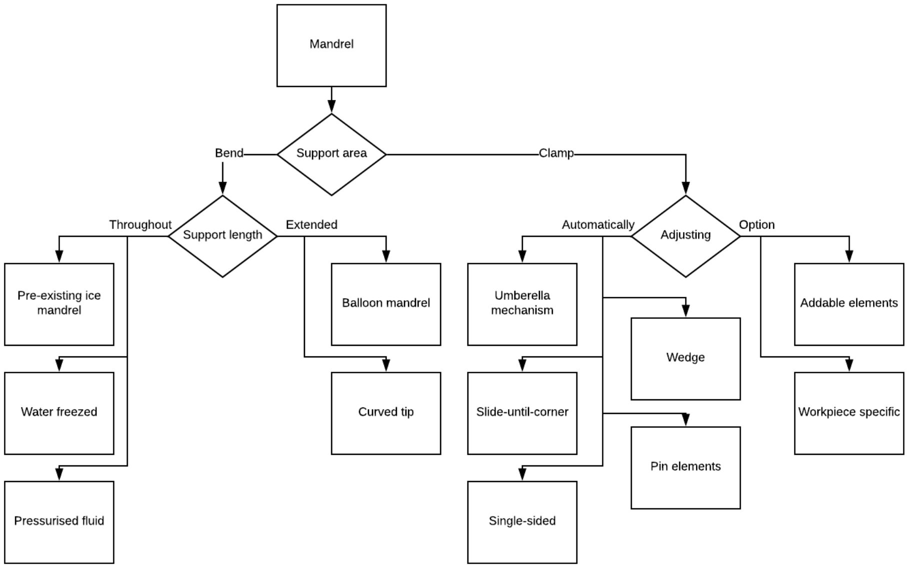

Figure 5.6: Concept chart for mandrels

Clamp	Mandrel (clamp)	Mandrel (bend)	Friction pattern
Cross-sectional vacuum			
Suction cup vacuum			
Current induced magnetism			
Penetration			
Weld			
Elastic connection	Umbrella mechanism	Balloon	Pyramid
Elastic continuous clamp	Slide-until-corner	Curved tip	Line
Press bending	Single-sided	Ice	Rough
Loose	Wedge	Water freezed	
Single-sided	Pin	Pressurised fluid	
2DBM	Addable		
3DBM 2500-A	Workpiece specific		
Knee-joint			

Table 5.1: Concept combination table

5.3 Sub-system set exploration

5.3.1 Fluid concepts

Most of the concepts relying on pressurised fluid are severely limited by the necessity to be tightly enclosed, which may be difficult to achieve in industrial mass production.

Therefore, one may eliminate all concepts relying on direct contact between fluid and the workpiece. Further, as the required time to pressurise large volumes, pressurised fluid concepts aimed at counteracting the clamping force may be eliminated. In addition to this, as the pressure created by vacuum is severely limited, one may eliminate the concepts relying on vacuum.

5.3.2 Mechanically adjusting concepts

The mandrels can either obtain support for sustaining the clamping by bridging the extrusion's sides or as moment and shear stress at the mandrel's the fixed end as a cantilever beam. Further, the mandrel is subjected to some tensile stress. Additionally, as the forces are excessive and the chamber space small, it is deemed more logical to apply forces inwards, with as few moving parts as possible. Based on these considerations, all concepts not bridging the extrusion's sides in a robust manner may be eliminated.

The leaf spring mandrel concept pulled from the R&D workshop relies on a weak second moment of area over the axis of bending. This prototype was reported to be successful for the 2DBM, but as the 3DBM will bend over two axes, the second moment of area over both of these axes must be weak, resulting in a too weak mandrel. The pin mandrel concept shares similar traits to the leaf spring mandrel. These concepts may be eliminated.

Interviewee B (interview A.4) aided in illuminating aspects of some of the sets (interview A.4), sharing experience from previous research and proposing a solution: the knee joint. This concept was well within the limits of the existing set of translational force application and was included.

5.3.3 Deformation concepts

The forces involved in the gripping mechanism are excessive, and for clamps relying on elastic deformation to transmit forces to the workpiece, any deformation would have to be rather excessive to have any effect. Further, if the ends of the workpiece are subjected to plastic deformation beyond the tolerance limits, the ends would have to be cut and discarded. Additionally, such deformation may cause an undesired stress distribution.

Excessive deformation may be acceptable if the deformed ends are to be cut anyways, or the cost associated with hindering deformation exceeds the cost associated with handling the deformation. The cost associated with handling such deformation may include process cost of cutting operation and material cost of discarded material. It is infeasible to avoid plastic deformation in transmitting the force involved, the elastic clamp concepts may be eliminated. Further, as the material constitutes up to 80% of the total cost of a product in mass production, the plastic deformation concepts may be eliminated.

5.3.4 Concepts not considered further

The friction surface concepts will not be considered further, as it is beyond the scope of this paper to test the patterns with computer tools (as it is very computationally expensive) and beyond the scope of this paper to test the pattern physically. Some mandrel concepts to support bends may still be feasible, but will not be considered further as they necessitate additional process steps and accommodations not currently available at the automotive parts manufacturer. Additionally, for academic, batch-of-one purposes, some clamp concepts may still be feasible, but will not be considered further as this project concerns industrial mass-production. The listed concepts may be feasible but will not be considered further:

- Friction pattern concepts
  - Pyramid pattern
  - Line pattern
  - Rough surface pattern
- Mandrel (bend)
  - Freezed fluid mandrel
  - Ice block mandrel
- Clamp concept
  - Penetration clamp
  - Weld clamp

5.4 Summary

The exploration of sub-system sets was processed as illustrated in Fig. 5.7. In Fig. 5.7, the stacked area graphs area the added amount of all sub-system concepts (indicated by the left vertical axis). The red line are the amount of system concepts, calculated by multiplying the sub-system concepts as in Eq. 5.1 (indicated by the right vertical axis).

It should be noted that the various sub-systems were developed concurrently, but presented linearly in this chapter to provide a structured presentation. Additionally, the elimination of concepts was based on numerous simple calculations which were considered to make the presentation unstructured if included. The remaining sub-system concepts are presented in Table 5.2.

Clamp	**Mandrel (clamp)**	**Mandrel (bend)**
2DBM	Workpiece specific	Balloon
3DBM	Addable elements	Curved tip
Knee-joint	Wedge	
Loose		

Table 5.2: Concept combination table after sub-system exploration

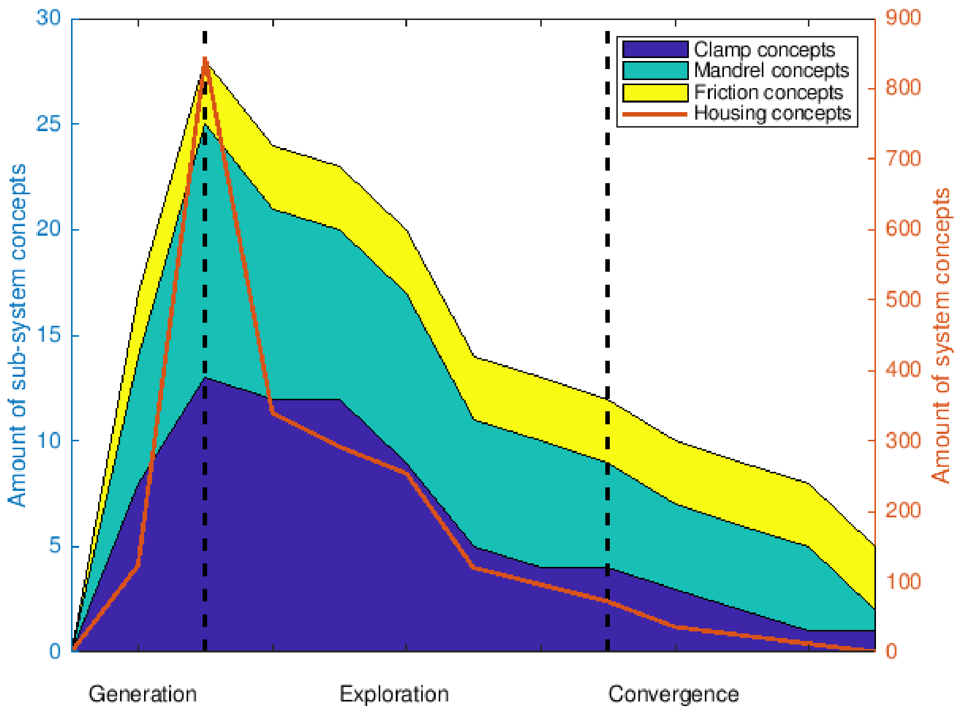

Figure 5.7: Reduction of concept amount over the duration of the project

Chapter 6

Concept convergence

6.1 Determine set intersections

6.1.1 Die

There are several considerations regarding the gripping mechanism's interaction with the die:

- The die for three-dimensional bending must provide support against the pitch and yaw.
- The pitch and yaw may be manipulated in conjunction, with the only limitation that the pitch will rotate the same direction (bending the workpiece over the die) for all bending operations while the yaw is free to switch direction between workpieces. However, in order to avoid springback, neither movement will reverse during a bending stroke.
- The horizontal symmetry of the 3DBM in relation to the horizontal symmetry of the workpiece, as illustrated in Fig. 6.1, accommodates flipping the workpiece relative to the 3DBM over the d.o.f. 2 before insertion to allow yaw the same direction for all bending operations.

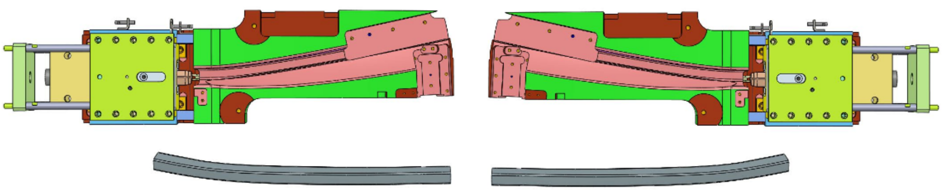

Figure 6.1: The horizontal symmetry of the 3DBM and the workpieces

- The fact that the pitch and yaw may be manipulated in conjunction provides freedom of design with regard to die orientation within the limitation of no negative pitch.
- The dies will be product specific and designed to provide maximum support to prevent sagging.
- The dies must be designed so that the workpieces are able to slide into the die if positioned slightly inaccurately.
- The 2DBM may bend two workpieces during one stroke by positioning the workpieces in parallel and concentrically with regard to the centre of the bending radius. The 3DBM does not have this possibility as it is impossible to place two equal objects in parallel and concentrically with regard to the centres of bending radii in three dimensions.
- Due to Newton's third law of motion, there is no fundamental difference in the force distribution between applying x amount of force on two opposite and facing sides of an object, and applying x amount of force on solely one side if the other side is rigidly supported.
- Cycle time could be reduced with unhindered insertion. Clamping strictly along the axis perpendicular to the axis of insertion could accommodate this, but may have implications on the support.
- One interviewee (interview A.9) stated that the robots for automatic handling of workpieces for the 3DBM 2500-A are flexible, and thus able to insert the workpieces from a desired angle. An unhindered insertion of the workpiece may potentially remove the positioning step, greatly reducing the cycle time.
- The workpieces are initially of constant cross-section, and the products will be designed so that it is acceptable that the cross-section over the gripping surface remains constant, as the extrusion will not be bent where it is gripped. That being said, one interviewee (interview A.6) stated that ”it has to be defined where you are allowed to have a pattern” due to considerations of joining components.

As the dies are product specific and provide optimal support and the force distribution is equal regardless of whether it is clamped on both sides or just one, it was decided that the clamping should be counteracted by the die. This requires a mandrel concept with freedom along the supported axis in order to transfer the forces to the die.

Due to the freedom of design of the die along the roll, gravity is the only difference between a housing accommodating insertion along the axis if d.o.f. 1 and clamping along the axis of d.o.f. 2 and a housing accommodating the opposite. Therefore, the dies should accommodate insertion from above. The positioning of the housing and mandrel should be along the axis of d.o.f. 4.

6.1.2 Friction area

The friction surface is given by the available area to be gripped. The friction force $F_{friction} \geq F$ is defined by the equation

$$F_{friction} = \mu F_{tensile}, \quad (6.1)$$

where μ is the friction coefficient and $F_{tensile}$ is the normal force defined by the equation

$$F_{tensile} = P_{contact} A_{contact}, \quad (6.2)$$

where $P_{contact}$ is the pressure over the area $A_{contact}$. This provides the minimum required contact pressure in relation to relevant design parameters. This relation is illustrated in the ToC in Fig. 6.2.

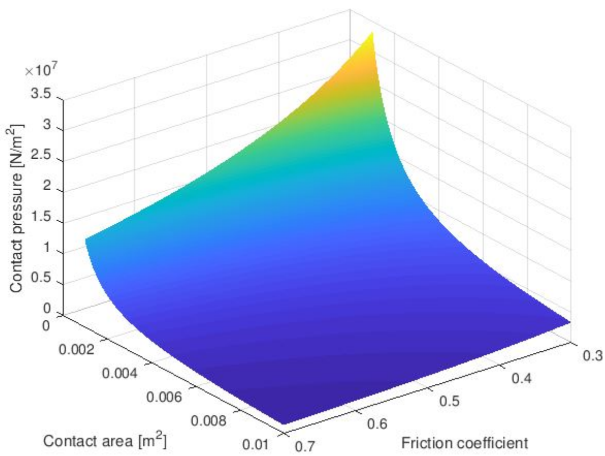

Figure 6.2: Trade-off curve of contact pressure, area and friction

The length of the friction surface was set to $40mm$ based on measurement of the technical drawing of the test profile illustrated in Fig. B.7, the CAD model of the test profile and its gripping surface in the existing solution.

Interviewee B (interview A.6) stated that you want to avoid that "(...) the whole area reaches yield" because "(...) if you continue to apply forces when it yields, it will become thinner, and will fracture right in the front of where you are gripping – in the transition between the thick and thin part". In essence, if "(...) everything continues to yield, then the gripping won't work". Because of this, the minimum area for a given pressure is important to calculate. According to the Von Mises criterion, the stress σ_e in the surface of friction may be calculated by the equation

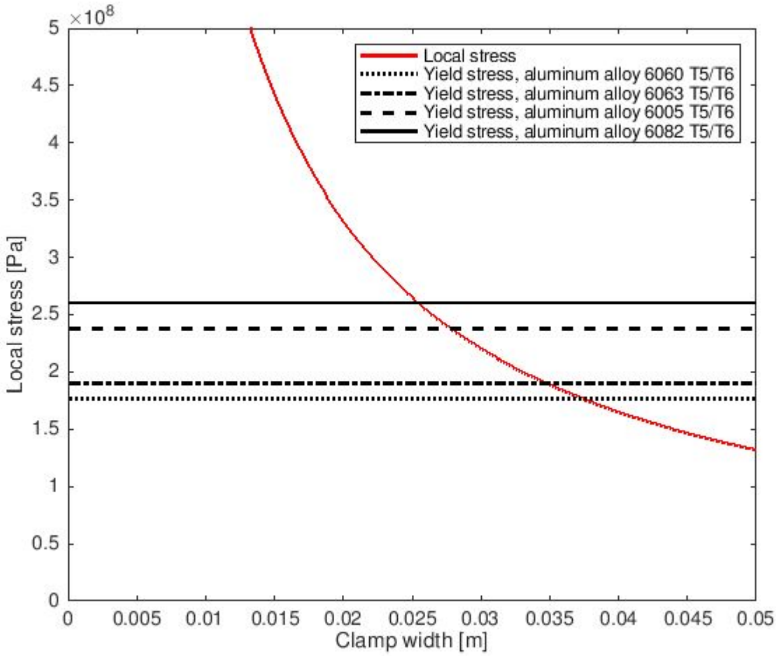

Figure 6.3: Trade-off curve of clamp width and local stress at clamping

$$\begin{aligned}\sigma_e &= \sqrt{\sigma_x^2 + \sigma_y^2 - \sigma_x\sigma_y + 3\tau_{xy}^2} \\ &= \sqrt{\frac{F_{pressure}^2}{A_{contact}^2} + \frac{3F_{tensile}^2}{A_{contact}^2}} \\ &= \frac{F_{tensile}}{A_{contact}}\sqrt{\frac{1}{\mu^2} + 3}.\end{aligned} \tag{6.3}$$

The surface stress in relation to the yield stress of the alloys to be bent provides the maximum contact pressure in relation to relevant design parameters. With values for clamping force, length, distribution and friction coefficient determined based on Fig. 6.2, minimum required clamp width is illustrated in the ToC in Fig. 6.3.

The possible combinations of friction surfaces are illustrated in the left side of the ToC in Fig. 6.4. This was related to a feasible area derived from the ToC in Fig. 6.3 and provided insight in what combinations of clamp, mandrel and support could provide sufficient friction surface. Further, it provided insight on the ratio of friction surface provided by the respective sections.

The researcher believed that the mandrel would contribute to the friction effects in the contact condition. This was exposed as an erroneous assumption. Interviewee B (interview A.6) stated that ”the problem is that there is a contradiction (...) You would like friction on the mandrel as well, so you get a bigger surface (...) but, the mandrel is entering a profile,

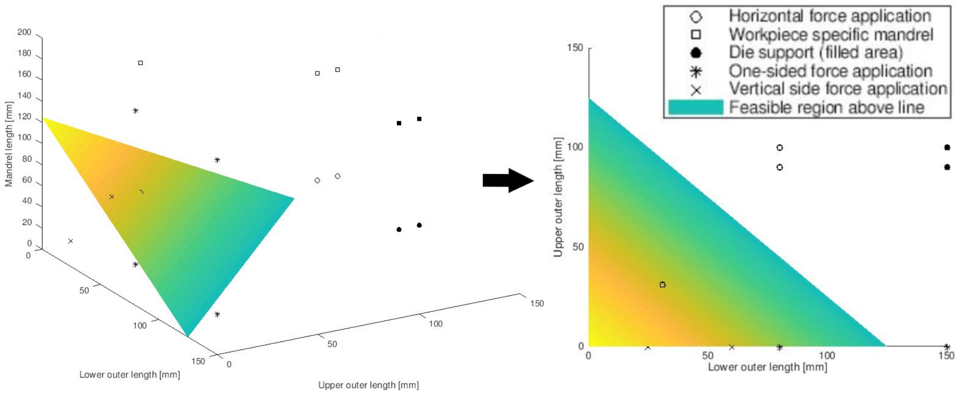

Figure 6.4: Combination of surface with mandrel (left) and without mandrel (right)

and then we would like it to be polished (...) Therefore, what is often done, is to make the mandrels completely smooth". This is to avoid chipping of aluminum. Based on this, it was deemed infeasible to rely on friction on the mandrel, and the ToC in Fig. 6.4 was flipped to remove the dimension of this friction effect.

6.1.3 Angle of force application

Both the knee joint concept and the loose clamp concept rely on a joint in an angle providing a great mechanical advantage. Based on the simple geometrical considerations

$$x = hyp \times \cos(\theta) = y \times \cot(\theta) \tag{6.4}$$

where x and y are the horizontal and vertical displacement, respectively, hyp is the joint length, and θ the joint angle, and based on the simplified work equation

$$W_{in} = F_x \times x = F_y \times y = W_{out}, \tag{6.5}$$

where F_x and F_y are the vertical and horizontal force, respectively, (and $W_{in} = W_{out}$ being work in and out, respectively, simply to indicate the simplifications in this calculation) the force ratio F_{ratio} may be calculated by the equation

$$F_{ratio} = \frac{F_y}{F_x} = \frac{x}{y} = \cot(\theta). \tag{6.6}$$

The angle varies for the knee joint concept, while the angle is set by the tracks for the loose clamp concept. Based on the calculations, the number of joints for the knee joint concept was reduced from three to two, resulting in a greater displacement ratio. The force ratio is illustrated in Fig. 6.5. It should be noted that for the loose clamp concept, the joint angle (and thus the force ratio) is fixed to a single point along the graph for the single joint.

The force ratio is unaffected by the joint length, so the joint length should be determined based on geometrical considerations. As indicated in Eq. 6.4, the joint length affects the horizontal and vertical displacement and should be carefully considered based

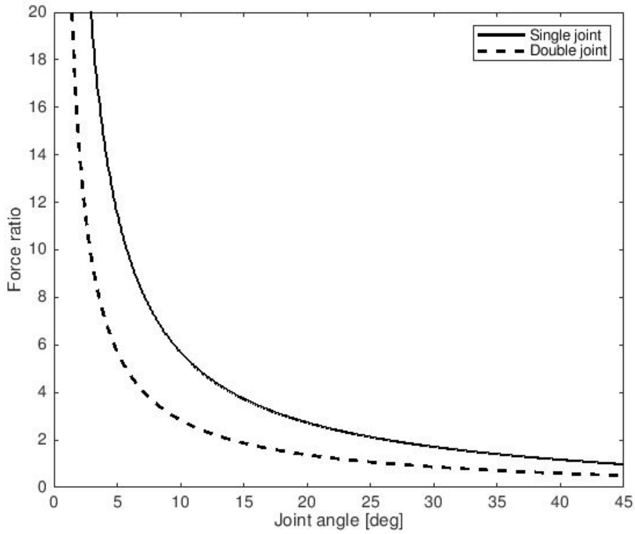

Figure 6.5: Relation between the force ratio and the knee-joint angle

on required and acceptable travel distance. For the loose concept, the travel distance can be calculated by Eq. 6.4 and for the knee-joint concept, by the equation

$$hyp = \frac{\Delta x}{\sin(\theta_2) - \sin(\theta_1)} = \frac{\Delta y}{\cos(\theta_2) - \cos(\theta_1)} \tag{6.7}$$

where θ_1 and θ_2 is the start and end angle, respectively.

Further, the relation between the angle of the clamps and their stress distribution should be explored. An Abaqus parameter study with variable angle was created, based on a framework established by Interviewee E (interview A.3). The framework is presented in Appendix. D. This indicated that the stress concentration was increased with increasing positive angle, as illustrated in Fig. 6.6.

6.2 Explore system sets

An overview of the iteration processes and the convergence of system sets is presented in Fig. 6.7. It should be noted that the concept iterations presented in this chapter discretise among the major variations within each set and numerous iteration steps were performed within each concept iteration step. The remainder of this section will be devoted to explaining the iteration process.

- **A:** The loose clamp concept relied on force transmission from the mandrel to the clamps, clamps wedging against the housing to provide a mechanical advantage. The mechanism for this transmission was gradually refined through static analyses by CAE, and difficulties regarding maintenance if the clamps were subjected

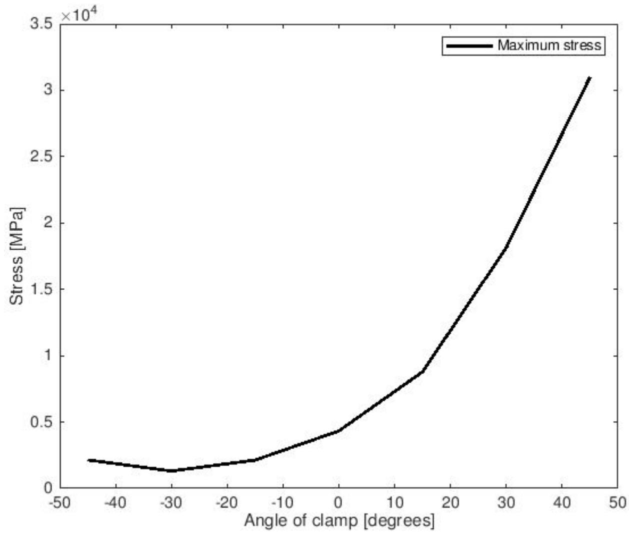

Figure 6.6: Abaqus parameter study of the clamp angle (negative values point towards house back wall) in relation to stress

to plastic deformation was addressed by implementing the T-tracks extracted from interviewee C (interview A.11).

- **AB:** The sets of A and B were merged by implementing the positioning mechanism of the 3DBM 2500-A. Geometric evaluation determined that this concept would grip over a too great grip-length.

- **ABC:** The sets of AB and C were merged by implementing a similar positioning mechanism and the continuous clamps of the 2DBM. The clamping mechanism integrated as a single part with simultaneous positioning and clamping (at a declining angle). The support of the clamp was positioned at the sides of the die, providing unhindered insertion of the workpiece. To reduce cost, the T-tracks in the housing/die-interaction was exchanged with quadratic, sideways tracks, with a translation decline of $5°$. This would include elements of the gripping mechanism of the 2DBM. This concept was predicted to be simple, robust and fast, but not flexible. The concept was gradually refined through dynamic simulations by CAE.

  During interview A.13, an erroneous assumption regarding the gripping mechanism of the 3DBM 2500-A was exposed.

  It was believed that the gripping mechanism of the 3DBM 2500-A (illustrated in Fig. 4.5) operated by moving the house, clamps and mandrel forward into position. Then, the house was fixed while the clamps and mandrel continue the forward motion (pushing the clamps downwards at a declining angle). The reality is that after moving to position the mandrel are fixed, the clamps are constrained in all degrees of freedom except downwards, and the house moves backwards (pushing the clamps downwards).

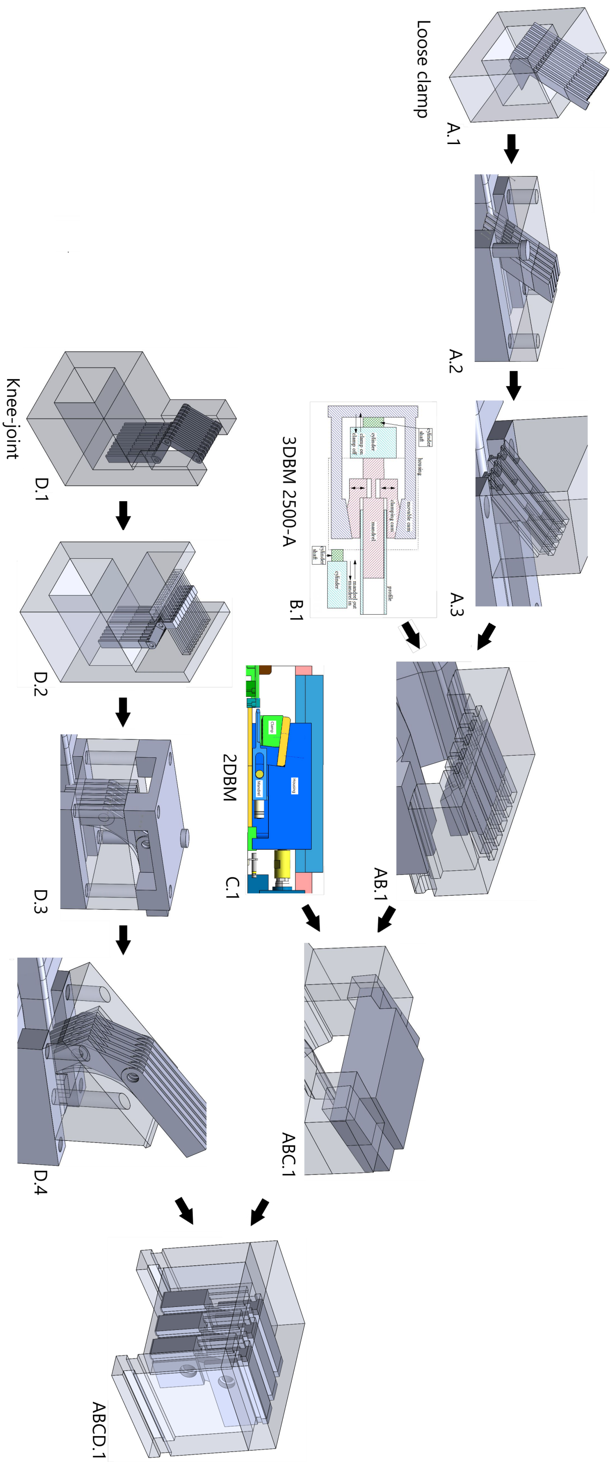

Figure 6.7: Overview of iteration process

The 3DBM 2500-A employs both these mechanisms, but the assumed gripping mechanism (accommodating the self-locking effect) is not initiated until after a firm grip has been established.

Gripping at a declining angle is not acceptable because ”(...) some material will be scraped”, and movement of the housing and clamping would have to be two separate operations, inhibiting the positive factors of the concept.

- **D:** The knee-joint concept relied on the joint to provide a great mechanical advantage. Based on the calculations illustrated in Fig. 6.5, the number of joints in the knee-joint concept was reduced from three to two. Geometrical considerations were employed to reduce the height and increase the stability of the concept. Additionally, the joint was evaluated to be slender and weak. The force transmission and the constraints of the joints and force transmission were gradually refined through static analyses by CAE. The weak-point of the construction was the rear of the clamp. Based on Fig. 6.6, the clamps were tilted, but the system was evaluated to be expensive, difficult to manufacture and difficult to maintain.

- **ABCD:** The sets of ABC and D were merged by implementing positioning at a declining angle of ABC. Additionally, the T-tracks with forces transmitted to a housing was implemented for constraining the joints. The number of clamps was reduced to three, and they were straightened to reduce the grip-length. To increase flexibility (and address problems with the clamps having a different mechanical advantage for different profiles) inserts were introduced, both on the clamps and to adjust the height of the housing.

  With the current die-configuration, the housing is changed with the die to have product-specific gripping. If that will be the case, the inserts will not be needed as the housing and clamps can be tailored to a greater degree. Because the die will be product-specific, the workpiece specific mandrel concept with a curved tip and die interaction as the 2DBM was evaluated to be the best mandrel concept. This accommodates swift mandrel change (the mandrel could be attached to the die and changed along with it) and fairly low production cost.

  Initially, housing was constructed to accommodate the T-tracks being produced by wire erosion. Wire erosion can achieve narrow tolerances but is rather expensive and the wire requires open access to both sides of the workpiece. Because of this, the house was designed as separate plates to be bolted together (with bolts throughout the side walls). This was modelled by CAE and the construction was evaluated to be too weak.

  Because of this, the housing was constructed to accommodate the T-tracks being produced by milling. Milling can construct the housing as one solid part, but it can not achieve narrow tolerances and leaves rounded edges near the walls. Because the greatest mechanical advantage lies close to the walls, the clamps would have to be rounded accordingly to fit.

  During communicated of this set in interview A.14, Interviewee A stated that:

  – ”It’s not more complex than what it has been”.

– ”Of course, if it is flexible, it needs to have certain limitations. It can’t cover everything”.
– ”(...) there’s not too much cost to produce something like that”.
– ”(...) it is much cheaper to machine such supporting pieces than to change the clamping every time”.
– ”(...) [clamp inserts] have to be sufficient if you are only going to make a few”.
– ”(...) you can 3D-print plastic [clamp] inserts, and it will become immensely flexible”.
– ”[it will] (...) make it more flexible [to have] (...) inserts in order to move the entire system upwards and downwards”.
– ”(...) if you were to use the die for multiple products [then] (...) you could have a steel die that is only the frame, and insert wooden dies into it. Then the system could be very flexible”.

Chapter 7

Detailed design

7.1 Full system definition

7.1.1 Overview

The final gripping mechanism is presented in Fig. 7.1. The gripping mechanism is constructed of a house (purple, yellow, red and orange), three knee-joints (pink, cyan and green), three clamp inserts (blue, darker blue and darkest blue) and three hydraulic actuators (light grey). It clamps the workpiece (salmon, only a section modelled) against the mandrel (turquoise, only a section modelled) and the die (dark grey, only a section modelled). All components with the same colour are identical and solid parts. It should be noted that some solid components may appear to be sectioned into more than one part: this is for computer modelling purposes only. The technical drawings of all components are presented in Appendix E.

7.1.2 Components

House

The solid house (purple) has three walls (one on each side and one in front) and a roof. A separate back wall (orange) is bolted to the open section in the back of the house. Three hydraulic actuators (light grey) are bolted to the back wall. The sides rest on house inserts (yellow) which rests on T-joints (red). The house insert and T-joint are connected to the house with bolts from below. The bottom of the T-joints is tilted in a $5°$ angle. The T-joints are inserted in T-tracks in the die (dark grey, only a small section of the actual die is presented in Fig. 7.1). The T-tracks are also tilted in a $5°$ angle.

All forces involved in the gripping mechanism are transferred through the house and into the die. Because of this, a solid house was necessary. Three parallel T-tracks are milled in the interior, both in the ceiling and the front wall. These are for translating the knee-joints.

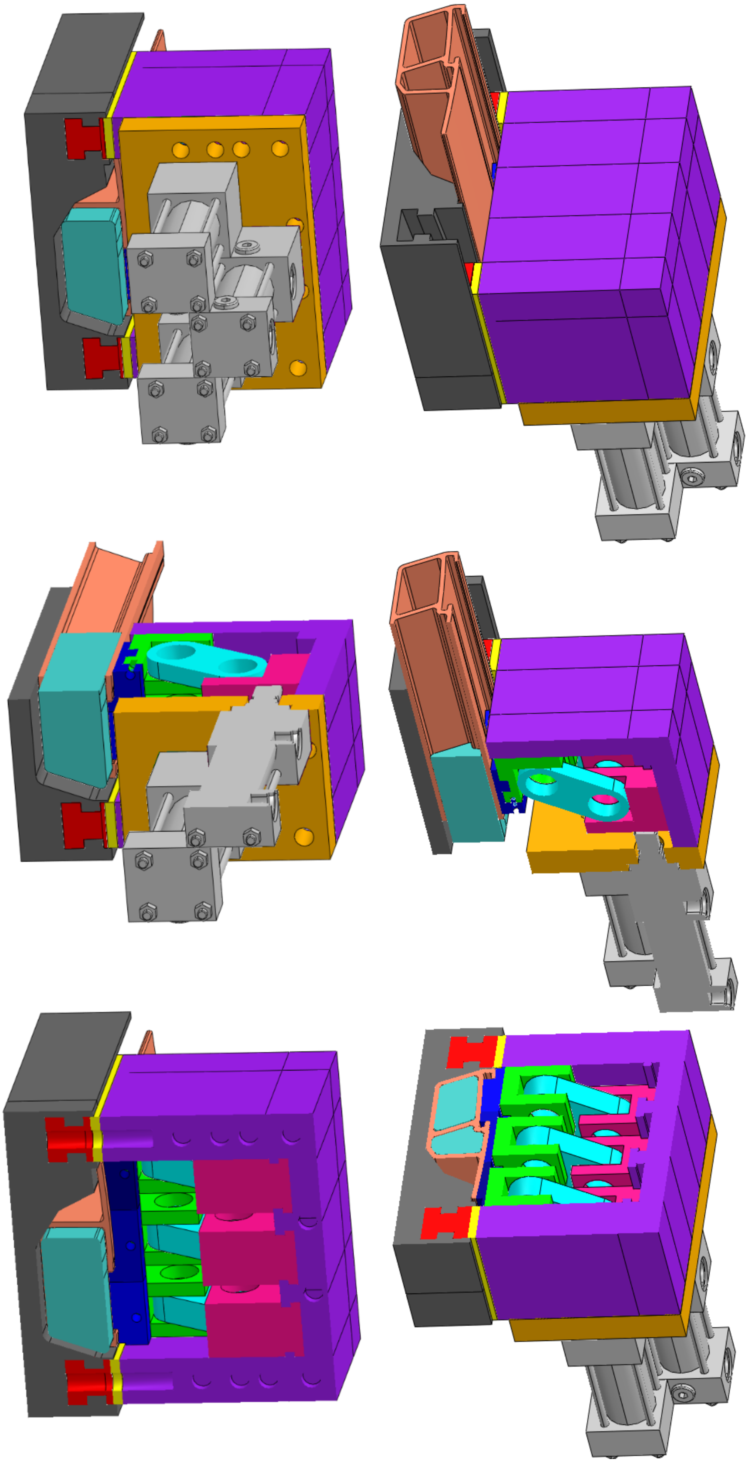

Figure 7.1: The novel gripping mechanism viewed from different angles with different cross-sectional cuts

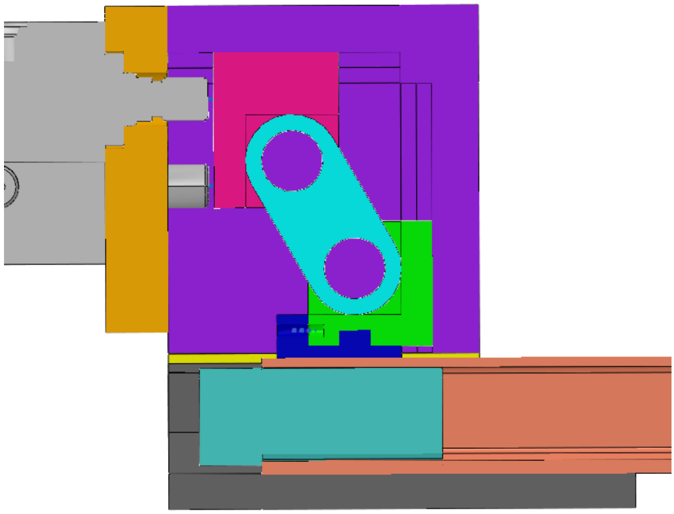

Figure 7.2: Cross-section cut of the gripping mechanism viewed from the side

Three double-acting hydraulic actuators are bolted to the back wall. One hydraulic actuator is connected to each of the knee-joints. The actuators are included in the model for ensuring geometric fit, but the interaction between the actuators and the knee-joints are not modelled as it would vary with the choice of actuator. The back wall is detachable by removing ten bolts and detaching the hydraulic actuators from the knee-joints.

The house should be translated to the correct position by an electrical actuator. This interaction was not modelled, as it would involve extensive assumptions regarding the die. When gripping is initiated, the actuator should provide the gripping mechanism freedom to translate. If the product slips, the obtained friction of the grip will translate the entire house. The tilted tracks will then provide a self-locking mechanism.

The T-tracks on which the house rests may be at product-specific height (for example, milled directly into product-specific dies) or at a fixed height (for example, milled into a standard frame structure in which the dies are inserted) – the die configuration is not decided and the gripping mechanism is designed to accommodate both.

Adjusting the height of the gripping mechanism housing to accommodate new products will be necessary if the 3DBM are designed with fixed T-tracks. The house inserts enable such adjustments. The house inserts are product-specific and designed with a simple geometry to be produced fast and at low-cost. T-tracks at product-specific height would eliminate the need for house inserts, which would enable the gripping mechanism house to be designed as a solid component including the T-joints.

Clamps

The knee-joint is constituted by a piston (pink), joint (cyan) and clamp (green). The piston and the clamp both have T-joints to be inserted in the T-track in the house. The T-joint of the piston is inserted into a T-track milled into the ceiling. The T-joint of the clamp is inserted into a T-track milled into the front wall. The joint connects the piston and the clamp with revolute joints in each end. There are three parallel knee-joints. The pistons of the double-acting hydraulic actuators attached to the back wall are connected to the back of the knee-joints' pistons.

Clamp inserts (blue, darker blue and darkest blue) are attached to the bottom of the clamps. The clamp inserts are product-specific and will interact with the product. The friction pattern should be milled directly into the clamp inserts. Each clamp insert is detachable by removing one bolt when the back wall is detached. For complex products, the clamp inserts must be product-specific to produce within tolerances. For products sharing profile traits, the clamp inserts may be employed for multiple products.

The knee-joints provide a great mechanical advantage at small angles. The hydraulic actuators provide constant pressure, which is necessary if thinning occur. This pressure should be regulated to avoid over-thinning if the pressure applied become too great due to the varying force ratio. The inner house T-tracks accommodate returning movement enforced by the double-acting hydraulic actuators.

The inner house T-tracks will be produced by milling. The edges near the corner of the front wall and the ceiling will be rounded because of the milling tool. The knee-joint pistons should be rounded accordingly. This was not modelled, as the radii will vary with the milling tool available.

Mandrel and die

The product is supported by a product-specific die (dark grey, underneath house). The die was not a component included in the product development project and its design is not decided. Certain assumptions regarding the gripping mechanisms interaction with the die were required. The validity of the assumptions was explicitly tested with the interviewees. The design of the gripping mechanism relies on the assumptions:

- The dies will be product specific.
- It is acceptable to use the dies as gripping support.
- It is acceptable to translate the gripping mechanism on T-tracks.
- The gripping mechanism must accommodate T-tracks of fixed height.

The interior of the workpiece is supported by a product-specific mandrel with a curved tip (turquoise). The mandrel should be connected to the die in a similar fashion to that of the 2DBM (with freedom of movement along the workpiece to insert and extract the mandrel, and freedom of movement upwards and downwards to transfer the forces from the clamps to the die. The mandrel should be translated along the d.o.f. 4 by double-acting hydraulic cylinders connected to the hydraulic system. The mandrel's interaction with the die was not modelled, as it would involve extensive assumptions regarding the die.

7.2 CAE analysis

7.2.1 Defining model

Material

The model of the gripping mechanism was assigned material properties of H13 Steel as defined in Table 4.1. Yield point was not defined in the model. Rayleigh damping was included in the material properties based on the eigenfrequency analysis. The model of the workpiece was assigned material properties of 6082 aluminum as defined in Table 4.1 and Fig. 4.6.

Mesh

The model was meshed with tetrahedral-elements. The mesh of the components are presented in Appendix F.

Revolute joints

The revolute joints were defined by modelling constructing a multi-point constraint (MPC) with beam connection between a master (reference point in the centre of the relevant hole) and a slave (the inner surface of the relevant hole). The MPCs in the model are presented in Appendix F. This will result in the displacement of the master to be rigidly distributed over the slave surface. The reference points of the holes to be jointed was then assigned a wire connection with a hinge joint assignment related to a coordinate system with the x-axis along the wire. This will result in the displacement of one reference point to transfer to the other, with a rotational d.o.f. along the x-axis (Dassault Systèmes, 2014, Ch. 35.2.3). To model the revolute joints in such a manner is a necessary simplification, as the friction effects of the joint would increase processing time. The bolts were dimensioned according to calculations by hand. All bolts were defined as revolute joints.

Translational joints

The translational joints were defined by defining friction surfaces. It is important to define friction surfaces for all surfaces expected to be involved in the interaction. That being said, increased friction surface area results in increased processing time. Further, friction surface interaction properties were defined. Lastly, all friction surface interactions were defined. In each interaction, the master/slave assignment had to be evaluated and defined. A master assignment was provided based on three considerations (with decreasing significance): the largest surface, the stiffest surface, and the surface with the coarsest mesh (Dassault Systèmes, 2014, Ch. 36.3.1). The friction surfaces interacting with the product were provided a friction coefficient of 1. The friction surfaces between bolted components were provided a friction coefficient of 0.5. The friction surfaces between sliding components were provided a friction coefficient of 0.3.

Actuators

The actuators were modelled by analysing the centre of gravity of the CAD model of the actuators. The model was assigned steel material properties and the centre of gravity was extracted. At this point (for all three actuators), MPCs with beam connections were made to the screw holes. MPCs with beam connections were made to the back of the back of the clamps, at the height of the MPC it would be connected to. These MPCs were connected with a wire connection with a rigid, axial rod assignment.

Boundary conditions and loads

The boundary conditions of the model were located as illustrated in Fig. 7.3. The bottom of the die (light blue) was fixed. The back wall (green) was fixed in d.o.f. 4. This boundary condition was assigned to avoid rigid body motion, but should be more accurately modelled when the gripping mechanism's interaction with the electrical actuator is determined. The mandrel back (red) was provided an unhindered d.o.f. upwards and downwards. The actuators (dark blue stippled lines) were provided connector displacement boundary conditions. The workpiece front (orange) was provided boundary conditions representing a symmetry plane over the cut, except it was allowed an unhindered d.o.f. along d.o.f. 4 to allow for stretching. Additionally, the workpiece front was subjected to a pressure load with a total force distribution.

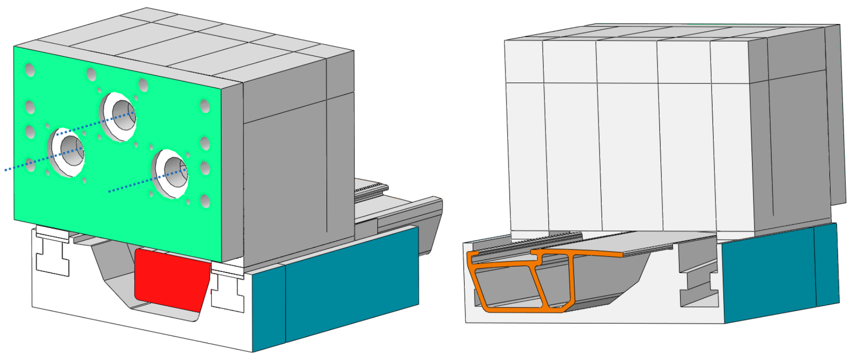

Figure 7.3: Boundary conditions of the model

The eigenfrequency analysis requires linearity, therefore the connector displacement and the pressure load were set to zero. The contact analysis was conducted in two steps: in the first step, the connector displacement was set to $0.7mm$ for all three actuators and the pressure was set to zero. In the second step, the connector displacement was held constant for all three actuators and the pressure was set to a total force distribution of $-200kN$.

7.2.2 Analyses

Eigenfrequencies

The eigenfrequencies of a system can be calculated by the equation

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}, \tag{7.1}$$

where k is stiffness and m is mass. Eigenfrequency analyses are useful because they:

- Establish what frequencies will have a self-propagating effect (relevant with regard to the operating frequencies of the actuators).
- Establish what frequencies to assign Rayleigh damping.
- Provide information visually regarding the erroneous modelling of joints and boundary conditions in a small amount of processing time.
- Provide information regarding the relation between the mass and stiffness of the construction.
- Establish the buckling pattern the construction is prone to.

An eigenfrequency analysis was conducted with a linear perturbation procedure frequency solver. The Lanczos method was applied, with default block size. Several low-frequency modes in the workpiece were present. These frequencies were neglected as they did not influence the gripping mechanism. Some low-frequency modes in the mandrel were present. These frequencies were neglected as the mandrel will be stiffer when attached to the die. The lowest frequencies were $\omega_1 = 2901.3Hz$ and $\omega_2 = 5834.1Hz$. The frequency modes are presented in Fig. G.1 and G.2 in Appendix G, respectively. The frequencies of the system are very high, well outside the frequency domain of all attached actuators.

Rayleigh damping assigns mass proportional damping α_1 and stiffness proportional damping α_2, which can be calculated by the equations

$$\alpha_1 = \frac{2\omega_1\omega_2}{\omega_2^2 - \omega_1^2}(\lambda_1\omega_2 - \lambda_2\omega_1) \tag{7.2}$$

and

$$\alpha_2 = \frac{2(\lambda_2\omega_2 - \lambda_1\omega_1)}{\omega_2^2 - \omega_1^2}. \tag{7.3}$$

A thumb rule states that $0.03 \leq \lambda \leq 0.07$ for metal structured with joints. The conservative values $\lambda_1 = \lambda_2 = 0.03$ is assigned. Therefore, the material properties were assigned a damping of $\alpha_1 = 116.3$ and $\alpha_2 = 6.9 \times 10^{-6}$.

Contact

The contact analysis was conducted with a static solver with nonlinear behaviour. The greatest relative displacement in the workpiece along the d.o.f. 4 was $0.212mm$. The smallest displacement in the workpiece along the d.o.f. 4 was $2.034\mu m$. The results of the workpiece deformation are presented in Fig. 7.4. The results of the workpiece stress distribution are presented in Fig. G.6 in Appendix G.

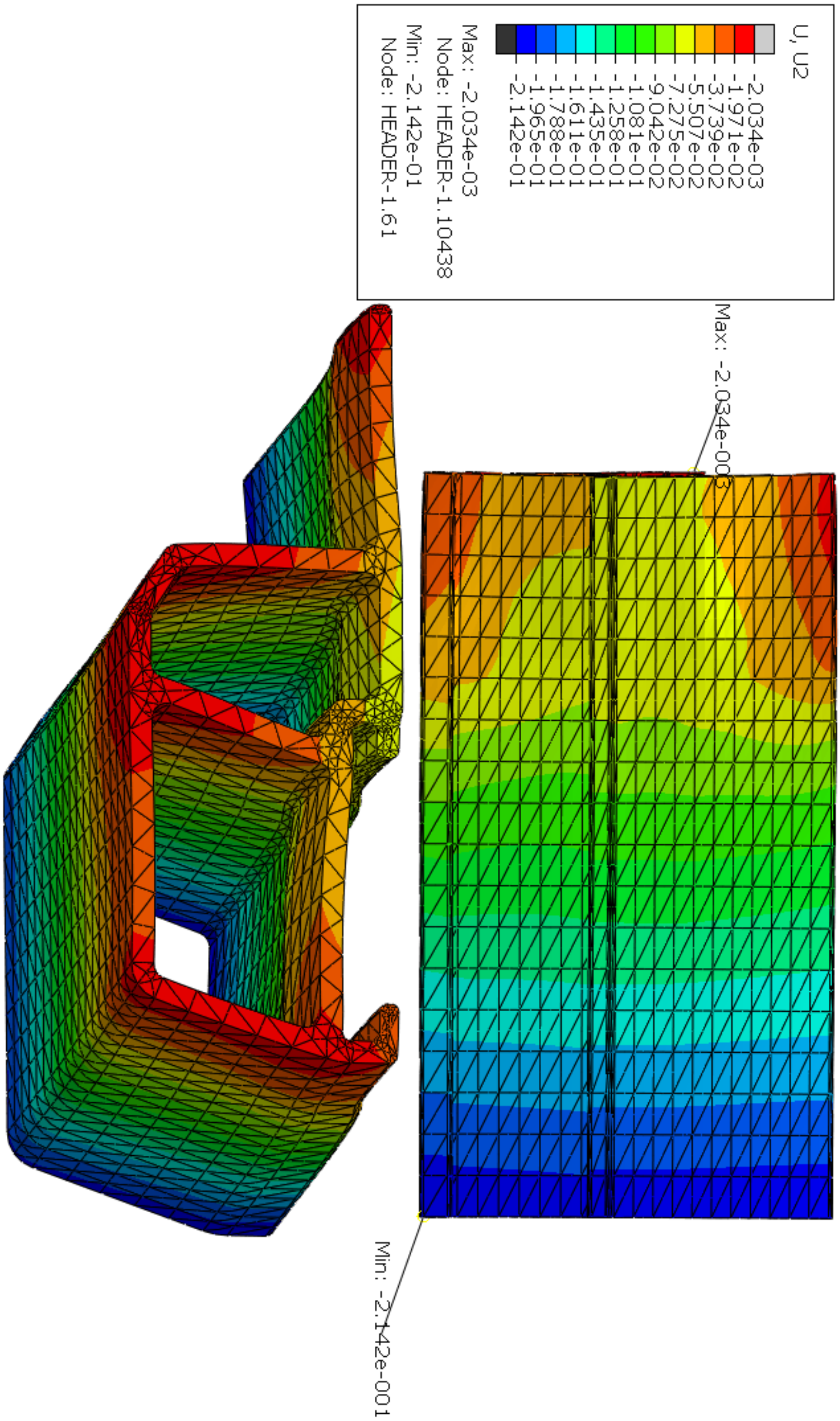

Figure 7.4: Deformation of the test product (deformation scale 20)

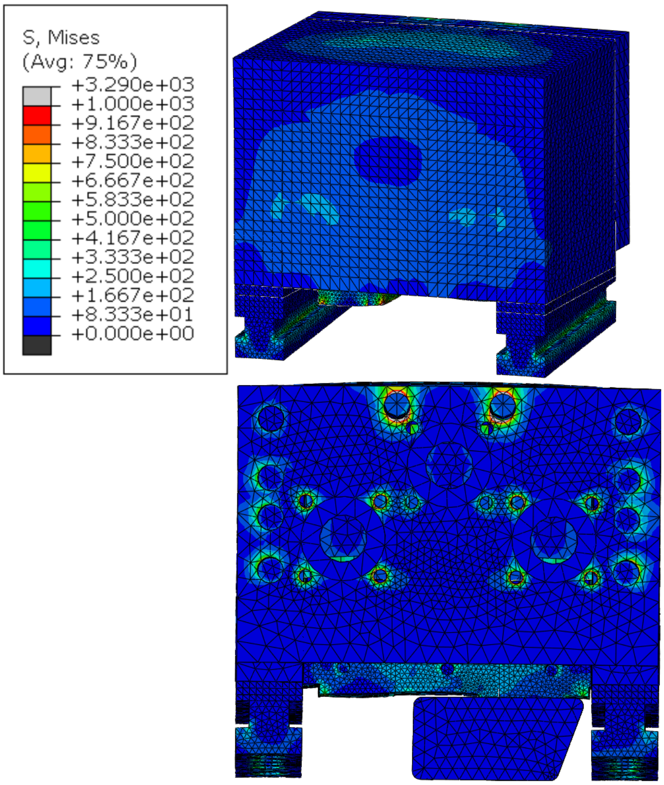

Figure 7.5: Stress distribution of the system (deformation scale 20)

The stress distribution in the gripping mechanism system is presented in Fig. 7.5. The deformation of the gripping mechanism is presented in Fig. G.3 in Appendix G.

There were regions of localised stress beyond the yield point in the back wall (localised stress of $3.29GPa$), the clamp inserts (localised stress of $3.16GPa$) and the knee-joint piston (localised stress of $1.81GPa$). The rest of the gripping mechanism was subjected to a localised stress ofmaximum $910MPa$, well below the yield point. The stress distribution in the back wall is presented in Fig. 7.5. The stress distribution in the knee-joints with and without the clamp inserts are presented in Fig. G.5 and G.4 in Appendix G, respectively.

The stress distribution in the workpiece suggests that the clamping was excessive. Reducing the clamping force would reduce the localised stresses. The deformations and stress distributions provide valuable information in the discussion regarding what areas of the gripping mechanism should be improved.

Chapter 8

Discussion

8.1 Discussion regarding design methodology

8.1.1 Design iterations

Discussion regarding the set-based and the concurrent aspect of the project

This PD process was a preliminary study preceding the actual development of the 3DBM. All elements of the 3DBM except the gripping mechanism were assumed to be designed as for the 3DBM 2500-A. Thus, the development of the gripping mechanism as a sub-system was isolated from the actual development of the rest of the system.

The isolation of the sub-system interfered with the set-based aspect of the project. Certain assumptions regarding this intersection between the gripping mechanism and die were necessary and any alterations were communicated and agreed upon with the relevant engineers through interviews.

The isolation of the sub-system also interfered with the concurrent aspect of the project. Considerations regarding all aspects of the product life cycle were established through interviews, but the relevant engineers were not yet engaged in the actual development of the 3DBM.

If the gripping mechanism concept presented in this paper is integrated into the 3DBM, the gripping mechanism and its interaction with the die should be tailored to the 3DBM. The knowledge gained throughout the PD process regarding the design space is presented in this paper to accommodate such a tailoring.

Discussion regarding computer tools for trade-off curves

The literature study identified an emphasis on test-before-design in order to close identified knowledge gaps before designing the part. Additionally, the literature study identified a lack of research regarding computer tools compatible with SBCE. Therefore, the way these tests were conducted in this project was through parameter studies in MATLAB and Abaqus, visualised as ToCs.

The parameter studies conducted in MATLAB were strictly math-based. These were extremely rapid and provided a lot of theoretical information of low resolution in ToCs. Additionally, the prototyping forced the researcher to identify the important design parameters.

The ToCs were often consulted to understand the intersection of various design parameters. The ToCs were employed interactively and iteratively. The design parameters were separated into different dimensions, and when the feasible area of the design parameters was narrowed, the limits on the dimension were narrowed accordingly.

The parameter studies conducted in Abaqus were strictly math-based as well, but to a far greater resolution than those in MATLAB. These were relatively time-consuming to develop and provided a lot of information of high-resolution in ToCs.

Gaining familiarity with Abaqus scripting was time-consuming, and an established framework for performing such parameter studies was required. When this was established, the tests provided unexpected and useful knowledge. Still, the same information could have been acquired by simply conducting multiple succeeding analyses (which is what the scripted parameter study automate).

These parameter studies allow for the plotting of any node (and as many nodes as desired) in the CAE model. Without an established framework for post-processing the information, plotting multiple nodes provided too much information to interpret. Because of this, the resolution of the information was simplified.

- **Observation:** The presented framework for parameter studies in Abaqus may provide useful, in-depth information, but the developer should be selective about what information to request and establish a framework for post-processing it.

Discussion regarding physical or abstract prototypes

Physical prototypes (mainly 3D printed or constructed with LEGO) were of much use early in the development process. LEGO was used to prototype constructions with joints in the concept generation phase. This was useful for brainstorming and to understand the 3DBM 2500-A. 3D printed components were used to prototype small-scale models of the received CAD models. This was useful to understand the geometry of the components.

After the concept generation, the researcher shifted towards a design-by-simulation philosophy. This is consistent with the findings of the literature study. Analytic prototypes with ToCs provided useful information regarding design parameter variations' influence on performance. CAD provided useful information regarding geometric considerations. CAE provided useful, in-depth information regarding the stress distribution in the components.

The reason for the shift towards a design-by-simulation philosophy may be that the forces involved were too extensive for physical prototypes. The forces and geometry could be scaled down, but to scale down the material properties would require extensive effort. Therefore, physical prototypes were evaluated to not be able to provide information regarding the relationship between design parameters and the strength of the construction.

Information regarding other aspects of the mechanism could be provided, mainly regarding the geometry and interaction between components. An emphasis on generating ToCs naturally involved abstract prototypes, which may have contributed to the shift towards a design-by-simulation philosophy. Additionally, CAD provides approximately the same information as 3D printing – just in a virtual realm and not a physical one. As 3D printed components were not expected to physically behave similar to the components they were to prototype, CAD was evaluated to provide more information in a more rapid manner.

- **Observation:** The researcher shifted towards a design-by-simulation philosophy after the concept generation phase.

8.1.2 Erroneous assumption of mandrel providing friction

Overview

The erroneous assumption that the mandrel provided friction could have been a cause for some rework. It was identified in interview A.6 while the sets were still rather wide. For clarification, the difference between the assumed and the actual contact conditions is:

- **Assumption:** It was believed that the mandrel would contribute to the friction of the contact conditions.

- **Reality:** The mandrel is explicitly designed with as little friction as possible in order to avoid shredding of aluminum.

Discussion regarding re-usable knowledge

The literature study identified an emphasis on generating re-usable knowledge. The erroneous assumption regarded the mandrel's contribution to the contact conditions. When exposed, a large portion of the available surface for gripping was diminished. There are several interesting aspects of this situation related to the generation and presentation of re-usable knowledge to reduce rework.

The literature study identified the principle of *integration by intersection*. Because of this, knowledge was generated to establish how each sub-system's available surface area contributed to the total contact condition (in relation to a feasible region). The literature study identified an emphasis on employing ToCs to visually establish knowledge. The knowledge was visually presented according to the structure of the knowledge. Each dimension of potential solutions (the contributors to the surface area) represented a dimension on the ToC. In this way, the contribution remained separated, but all available manners of integration were represented by their intersection.

The literature study identified an emphasis on reasoning sets as ranges. This influenced the handling of the erroneous assumption, as the available surface area of the mandrel were already reasoned as a range which might be diminished. Further, the literature study identified the principle of *establishing feasibility before commitment*. Because of this, there had been made no large commitment, and the assumption was communicated and exposed. When the erroneous assumption was exposed, one dimension of the solution was infeasible. Had the knowledge been structured in a way where all contributions were tangled, new knowledge would have to be established. With the separated structure, the dimension of the mandrel's available surface area was eliminated by simply pivoting the ToC, as presented in Fig. 6.4. It is important to note that the both sides of the figure are the same ToC, only pivoted. This pivot automatically moved the concepts relying on the friction of the mandrel to be moved into the infeasible region. This way, the knowledge established regarding the remaining contributors remained valid.

- **Suggestion:** For math-based trade-off curves intended for interactive communication through computer tools, structure each parameter in separate dimensions and present potential solutions for integration through their intersection.

8.1.3 Erroneous assumption of gripping at a declining angle

Overview

The erroneous assumption that gripping at a declining angle was acceptable could have been the cause of a great amount of rework. It was identified in interview A.13 when there were only two clamping concept sets remaining. A lack of understanding regarding the gripping mechanism of the 3DBM 2500-A resulted in this assumption. For clarification, the difference between the assumed and the actual mechanism is:

- **Assumption:** It was believed that the gripping mechanism of the 3DBM 2500-A operated by moving the house, clamps and mandrel forward into position. Then, the house was fixed while the clamps and mandrel continue a forward motion (pushing the clamps downwards at a declining angle). This ensures gripping at a declining angle. This operation is possible, given the erroneous assumption that gripping at a declining angle is acceptable.

- **Reality:** The gripping mechanism of the 3DBM 2500-A operates by moving the house, clamps and mandrel forwards into position. Then, the mandrels are fixed, the clamps are constrained in all degrees of freedom except downwards, and the house moves backwards (pushing the clamps downwards). This ensures gripping strictly downwards.

Discussion regarding set robustness

The literature study identified an emphasis on keeping the sets robust by including established solutions in the set. The established solutions in this project were the gripping mechanism of the 2DBM and that of the 3DBM 2500-A. There are several interesting aspects of this situation related to how the researcher's erroneous assumption regarding the gripping mechanism of the 3DBM 2500-A manifested in various parts of the sets.

At the beginning of the *concept convergence* stage, two of four clamp concepts had a latent fault of the erroneous assumption: the clamping concept of the 3DBM 2500-A and that of the initial loose clamp concept. The literature study failed to identify any research discussing design fixation in relation to the pulling of design concepts in SBCE. In retrospect, design fixation may be identified in the development of the loose clamp concept. The loose clamp concept was essentially the clamps of the 3DBM 2500-A separated from the mandrel with a different force application.

The pitfalls of design fixation are emphasised in this situation, where the design on which the researcher was fixated on was misunderstood. Additionally, the literature study failed to identify a framework for concept set generation, thus the five-step model proposed by Ulrich and Eppinger (2012) was adapted and employed. The five-step model was adapted by eliminating the *clarify the problem* step. The model accommodated a systematic structuring of the sets through concept classification trees and a concept combination table which provided a structured visualisation aiding the narrowing of sets.

- **Observation:** The five-step model for concept generation may be easily adapted to SBCE. This provides a visual structure for the sets.

This model proposes an external search (concept pulling) before an internal (concept generation). This may be a double-edged sword, as the external search may inspire more concept to be generated in the internal search, but these concepts will be prone to design fixation.

- **Suggestion:** A portion of the concept generation should occur before concept pulling in order to reduce design fixation.

The literature study identified an emphasis on generating broad sets to be narrowed in order to increase set robustness. Naturally, with broad sets, every concept may not be explored in detail concurrently. Further, the literature study identified an emphasis on pulling design concepts in order to increase set robustness. The 3DBM 2500-A was an established solution, and the apparent similarities to the gripping mechanism of the 3DBM 2500-A lent credence to the loose clamp concept. Because the sets were broad and the solutions assumed established, the sets of the 3DBM 2500-A and the loose clamp concept were not thoroughly explored until the *concept convergence* stage. In other words, as the sets were established with measures reported to increase set robustness, the sets were assumed robust. This reduced the actual robustness of the sets.

- **Observation:** The framework for establishing set robustness may provide a false sense of security regarding the actual robustness of the sets.

Discussion regarding a framework for reducing rework

Interestingly, the loose clamp concept and the 3DBM 2500-A unwittingly accommodated the backwards motion required in the same manner that the actual mechanism of the 3DBM 2500-A accommodates gripping at a declining angle. Because of this, the erroneous assumption was not exposed during communication of the sets.

The erroneous assumption was exposed during the *concept convergence* stage. Converging clamp sets were merged at their intersection. First, the loose clamp concept and the 3DBM 2500-A sets were merged. Secondly, an attempt to merge this set with that of the 2DBM was initiated, as the assumption implied an intersection of these sets in the motion of the housing. The resulting merged set did not accommodate the strictly downwards grip and was exposed during subsequent communication of sets.

The scope of this project was to conduct a case study within the framework established by SBCE, not to generate any comparable situations in a case study within a framework with a point-based approach. That being said, it is worth noting that as the loose clamp concept and the 3DBM 2500-A unwittingly accommodated the backwards motion, one may argue that even in a project with a point-based approach, there would be limited rework.

The literature study identified the principle *creating and exploring multiple concepts in parallel*. This is a fundamental part of the framework established by SBCE that is not present in frameworks established by point-based approaches. The way this situation was handled within a set-based framework was that remaining positive factors of the (faulty) set were transferred to the parallel set, and the sets were merged into one.

- **Observation:** Merging similar sets actively aid to identify the sets' positive and negative factors.

Discussion regarding computer tools for communication in SBCE

The literature study identified an emphasis on visual communication in SBCE. The researcher's erroneous assumption regarding the gripping mechanism of the 3DBM 2500-A was exposed during such visual communication, adding credence to its potency. Still, the assumption was not exposed before late in the development process. There are several interesting aspects of this situation related to the use of computer tools for communication in SBCE.

A detailed introduction of the gripping mechanism of the 3DBM 2500-A was provided by interviewee B (interview A.2). This was communicated through the original CAD model, explained with moving sub-systems relative to one another. The initial process of gathering knowledge is extensive and must be recorded. The interviews were audio-recorded and sketches were photographed and digitally stored. The audio-recordings and photographs were often consulted to ensure an understanding of the concepts explained. There were no visual recording of interactions with CAD models.

- **Suggestion:** Screencast communication performed by visual interaction with computer tools.

The CAD model of the gripping mechanism of the 3DBM 2500-A obtained from the customer was of a file format not supporting assembly constraints (and thus relative movement). This was because there was no established framework for sending files of such excessive size (both memory stick and e-mail failed). This inhibited further exploration of the relative movement of the mechanism.

- **Suggestion:** Pull prototypes of concepts to the greatest available resolution.

During development, the erroneous assumption was not exposed during communication of sets as the previous iterations unwittingly accommodated the backwards motion required (in the same manner that the 3DBM 2500-A accommodates gripping at a declining angle). This communication of sets was performed visually with sketches, which is not inherently capable of conveying motion. Interestingly, the erroneous assumption was exposed during the first communication where CAD models were used as a visual medium. This might suggest that CAD models are effective tools for visual communication if employed correctly.

- **Suggestion:** Communicate systems in motion with prototypes capable of conveying the motion.

Although communication was performed by sketches, crude CAD models of various concepts were already developed. One factor that influenced the choice of sketches as preferred visual medium above CAD models is that the researcher chose an exploratory approach to the interviews (and thus the communication of sets). In order to achieve this, an unstructured approach to the interviews was employed and as few constraints as possible imposed the interviewee. CAD models were evaluated to be too constraining. This was partly because approaching with a computer may ”formalise” an otherwise unconstrained atmosphere. More importantly, it was because CAD models are less flexible than sketches, and may impose constraints on the perception of design space.

More often than not, the interviewee would sketch over the interviewer's sketches in order to convey ideas or correct assumptions. This sketch could be further manipulated in a sense of visual two-way communication and iterative prototyping. The literature study failed to identify any available virtual tools to communicate in such an iterative way.

- **Suggestion:** Establish a framework for a computer tool to enable visual, set-based, two-way communication.

Another important factor which may have influenced the choice of sketches as preferred visual medium above CAD models is that the models were evaluated to be too crude to present to the customer. The literature study of design methodology identified the necessity to know the audience of the prototypes. In this project, the hierarchical position of the customer relative to the researcher was rather diffuse. The customer was (by both the researcher and the customer) considered to be a co-developer of the system – in that sense, it would be logical to use prototypes to get feedback of evolving design. Still, the customer invested time and resources into the PD – in that sense, it would be logical to use prototypes to convey progression.

In projects with a point-based approach, CAD models often provide a clear indication of progression as it is often an integrated prototype of the entire project. In this project, with a set-based approach, CAD models did not hold this function. The prototyping concerned numerous crude, focused CAD models exploring different areas of the design space, rather than one comprehensive. Additionally, the literature study regarding design methodology identified that projects with set-based approaches converge slowly.

As this project was a case study of SBCE in a company not familiar with the development methodology, these deviations from the traditional projects with point-based approaches could have been interpreted as a lack of progression.

A lack of confidence that the true progression of the project would be conveyed by such crude prototypes may have been a (subconsciously) influencing factor in why sketches were preferred above CAD models; sketches communicate the evolving design without claiming to be an indicator of progression.

- **Suggestion:** Communicate clearly the role of virtual prototypes in the project to gain confidence that the right information is being conveyed.

8.2 Discussion regarding the product

8.2.1 Discussion regarding the knee-joint components

Several clamp concepts iterations resulted in the knee-joint solution implemented in the gripping mechanism. The knee-joint concept with three parallel clamps was considered to be the best solution because:

- It provides and sustains great forces with a great force ratio.
- The three parallel clamps accommodate even grip distribution with variations in different sections of the profile, as the grip will vary accordingly.
- The three parallel clamps accommodate flexibility to grip different profiles with the same gripper.
- It accommodates changing a few, low-cost inserts for new products. Some inserts may be used for multiple standard profiles.
- It is relatively easy to maintain.
- It is a relatively safe process.

The mechanical advantage of the knee-joints is varying with the angle, and provide a great force ratio at small angles. There are several implications due to the varying mechanical advantage:

- Gripping at positions of great mechanical advantage is most effective and forceful. The house inserts, clamp inserts and die should be designed to take advantage of this.
- Small variations in the profile may cause great variations in the mechanical advantage. The house inserts, clamp inserts and die should be designed with considerations regarding variations to grip as desired.
- Thinning in the gripping surface may provide the gripping mechanism freedom to grip more extensively. If the hydraulic pressure is not regulated, the increasing mechanical advantage may result in further thinning. Therefore, there should be established a regulation system to avoid such occurrences.
- The gripping mechanism is able to provide great forces but only as great as it's components can sustain. The house inserts, clamp inserts and die should be designed to sustain the greatest forces involved considering variations.

The clamp inserts will be the part of the clamping which interacts with the product. The clamp inserts will likely have to be replaced often, similarly to the friction pattern inserts of the 3DBM 2500-A. Each clamp insert is easily detached from the knee-joint by removing a single bolt. The clamp inserts are designed to be produced fast and at low-cost. The production cost may be further reduced by design considerations regarding the grip surface requirements of each product.

The CAE analyses indicated regions of yield in the clamp inserts in certain areas of workpiece contact. These areas were located in the front corners of the clamp inserts, most notably towards the edges of the workpiece. This suggests that the clamp inserts' friction surface was not sufficiently tailored to the workpiece. Physical testing during prototyping of clamp inserts could refine the friction surface and reduce localised stress. Additionally, the results indicate that the stresses were not distributed to the back of the clamp inserts. Locating the revolute joint of the knee-joint clamp more towards the back may achieve a more even distribution.

The CAE analyses indicated localised regions of yield in the knee-joint pistons located at the front edges. Similar to the clamp inserts, the results indicate that the stress is not distributed towards the back of the knee-joint pistons, which may be achieved by locating the revolute joint more towards the back of the knee-joint pistons. The localised stress may be further reduced by rounding the edges.

- **Design consideration:** The design will be improved if the localised stress in the knee-joints is reduced. This is accommodated by re-positioning the revolute joints to distribute the forces more evenly.

8.2.2 Discussion regarding the house components

Several house concept iterations resulted in the solution implemented in the gripping mechanism. The house concept implemented was considered to be the best solution because:

- It is a solid component, which makes it robust and easy to maintain.
- It encloses the mechanism, resulting in a safe process.
- Enclosing the joints results in the house being subjected to compression rather than stretching. This makes the house more durable as it is less exposed to fatigue.
- The durability is increased by enclosing the mechanism from dirt. This also reduces maintenance needed (but exposed joints would be much easier to access during maintenance).

The house back wall as a separate component (compared to implementing the wall in the solid house) was necessary due to manufacturing considerations regarding the milling of the inner house T-tracks.

Implementing the house back wall in the gripping mechanism at all is necessary mainly because the researcher did not manage to identify hydraulic actuators which could geometrically fit to be attached to the solid house ceiling. Additionally, the house back wall stiffens the structure, but other design considerations could address the structural implications of eliminating the component.

The house back wall could be eliminated all-together if fitting actuators were identified, which would greatly improve access to clamp inserts, improve maintainability and reduce production costs. Exposing the mechanism to the environment might result in a less safe process and more dirt in the system.

The CAE analyses indicated localised regions of yield in the back wall located in the bolt holes connecting the actuators. The regions are extremely localised, which might be an indicator of a too coarse mesh. Additionally, it suggests that distributing the forces from the actuators to a greater degree could reduce the localised stress. Positioning the actuators to provide forces without attaining a moment may reduce the localised stress as well. Geometrical considerations of the hydraulic actuators are the reason for the actuators' misaligned positions. Identifying hydraulic actuators which enables aligning them (or eliminating the house back wall and connecting the actuator to the solid house ceiling) would be beneficial with regard to stress distribution.

The house inserts may be detached from underneath. This implies that the entire gripping mechanism must be separated from the T-tracks. That being said, the gripping mechanism will have to be separated for each product if inserted into T-tracks milled directly into a product-specific die as well (because the die is changed).

- **Design consideration:** The design will be improved if the house back wall is removed. This is accommodated by identifying actuators which geometrically fit to be bolted to the solid house ceiling.

8.2.3 Discussion regarding the mandrel

Several mandrel concept iterations resulted in the workpiece specific mandrel with curved tip solution. The mandrel concept was considered to be the best solution because:

- A product-specific mandrel is required to produce within tolerances.
- A solid product-specific mandrel is not much more expensive or time-consuming to produce than product-specific mandrel inserts.
- A solid mandrel is robust and durable.
- A solid mandrel is swifter to replace than several mandrel inserts.

The mandrel should interact closely with the die (or standard frame structure) rather than be a part of the gripping mechanism. This is because the mandrel will always be product-specific while the clamp inserts and house inserts (though primarily being product-specific) may be used for several products sharing traits. Implementing the mandrels in the gripping mechanism would require always replacing parts of the gripping mechanism, ruining the opportunity provided by the flexibility of the system. Because of the mandrel's close interaction with the rest of the 3DBM, the mandrel was not modelled in detail as it would require too many assumptions regarding its design and impose restrictions on the design space.

Chapter 9

Conclusion and further work

9.1 Conclusion

A literature study of set-based concurrent engineering has been conducted. The literature study identified the SBCE principles:

- **Principle:** Mapping the design space
- **Principle:** Integration by intersection
- **Principle:** Establishing feasibility before commitment
- **Principle:** Creating and exploring multiple concepts in parallel
- **Principle:** Strategic value research and alignment

The SBCE process model for product development ”the baseline model” was identified, as were related activities. The stages and activities of the baseline model are:

- **Stage:** Value research
  - **Activity:** Classify project type
  - **Activity:** Explore customer value
  - **Activity:** Align with company strategy
  - **Activity:** Translate customer value to designers
- **Stage:** Map design space
  - **Activity:** Identify sub-system targets
  - **Activity:** Decide on level of innovation to sub-systems
  - **Activity:** Define feasible regions of design space

- **Stage:** Concept set development
  - **Activity:** Pull design concepts
  - **Activity:** Create sets for each sub-system
  - **Activity:** Explore sub-system sets: prototype and test
  - **Activity:** Capture knowledge and evaluate
  - **Activity:** Communicate set to others
- **Stage:** Concept convergence
  - **Activity:** Determine set intersections
  - **Activity:** Explore system sets
  - **Activity:** Seek conceptual robustness
  - **Activity:** Evaluate sets for lean production
  - **Activity:** Begin process planning for manufacturing
  - **Activity:** Converge on final set of sub-system concepts
- **Stage:** Detailed design
  - **Activity:** Release final specification
  - **Activity:** Manufacturing provide tolerances
  - **Activity:** Full system definition

This paper has presented a case study of set-based concurrent engineering at an automotive parts manufacturer applied to a product development process of a novel gripping mechanism for the 3DBM. The product development process was structured according to the stages of the baseline model. The product development was conducted according to the principles and activities identified. The literature study identified case studies of product development within the SBCE framework. The literature study identified three main research gaps. Observations and unambiguous suggestions regarding the research gaps based on the experience from the case study were presented:

- **Research gap:** A structured framework for the generation of sub-system sets in SBCE
  - **Observation:** The five-step model for concept generation may be easily adapted to SBCE. This provides a visual structure for the sets.
  - **Observation:** The framework for establishing set robustness may provide a false sense of security regarding the actual robustness of the sets.
  - **Suggestion:** Pull prototypes of concepts to the greatest available resolution.
- **Research gap:** Discussions regarding design fixation in relation to extracted concepts
  - **Observation:** Merging similar sets actively aid to identify the sets' positive and negative factors.

- **Suggestion:** A portion of the concept generation should occur before concept pulling in order to reduce design fixation.

- **Research gap:** How to implement computer tools for product development in SBCE
  - **Observation:** The researcher shifted towards a design-by-simulation philosophy after the concept generation phase.
  - **Observation:** The presented framework for parameter studies in Abaqus may provide useful, in-depth information, but the developer should be selective about what information to request and establish a framework for post-processing it.
  - **Suggestion:** Communicate clearly the role of virtual prototypes in the project to gain confidence that the right information is being conveyed.
  - **Suggestion:** Establish a framework for a computer tool to enable visual, set-based, two-way communication.
  - **Suggestion:** Communicate systems in motion with prototypes capable of conveying the motion.
  - **Suggestion:** Screencast communication performed by visual interaction with computer tools.
  - **Suggestion:** For math-based trade-off curves intended for interactive communication through computer tools, structure each parameter in separate dimensions and present potential solutions for integration through their intersection.

This product development process has considered 845 system concepts and concluded with suggesting a novel gripping mechanism. The novel mechanism's three parallel knee-joints, clamp inserts and house inserts accommodate adjusting the gripping mechanism to new products at low cost. Technical drawings of the novel gripping mechanism's components have been presented.

The novel gripping mechanism was analysed through a CAE tool. Neglecting localised stress, the novel gripping mechanism performed within the requirements:

- The novel gripping mechanism is capable of fixing the test profile subjected to a tensile force of $200kN$ with $2.034\mu m$ slippage in the test profile's point of minimum tensile translation, twice as good as the requirements.

- The lowest natural frequency of the novel gripping mechanism was $2901.3Hz$, well above the operating frequencies of actuators directly connected to the gripping mechanism and well within the requirements.

Based in the results of the analyses, design considerations for optimising the novel gripping mechanism were presented:

- **Design consideration:** The design will be improved if the localised stress in the knee-joints is reduced. This is accommodated by re-positioning the revolute joints to distribute the forces more evenly.

- **Design consideration:** The design will be improved if the house back wall is removed. This is accommodated by identifying actuators which geometrically fit to be bolted to the solid house ceiling.

9.2 Further work

9.2.1 Further work regarding SBCE

In order to ease the implementation of set-based concurrent engineering in industries, there are several aspects of the design methodology which requires further research. Most importantly, industrial case studies of SBCE are necessary to enlarge the knowledge base regarding practical applications of SBCE. This paper has presented such an industrial case study, identified two research gaps further case studies could focus upon and presented observations and suggestions regarding these research gaps which could serve as a starting point for such case studies:

- There is a need for establishing a technological framework for co-development and communication within the principles of SBCE. This paper has presented suggestions elements to consider for further research with such an aim.
- There is a need for a structured framework for concept generation of sub-system sets in SBCE. This paper has presented an adaption of the five-step model and suggested elements to consider for further research with such an aim.

9.2.2 Further work regarding the 3DBM

As this paper has regarded a preliminary product development project, it assumed that all components of the 3DBM except the gripping mechanism will be transferred from the 3DBM 2500-A. The 3DBM is going to be further developed and constructed. The level of innovation for the entire machine should be decided to establish what elements of the 3DBM 2500-A that will be transferred to the construction of the 3DBM, and what components will be novel. The intersection between this project and the novel components should be established in order to decide what elements of the gripping mechanism may be implemented in the actual development of the 3DBM. If it is decided to implement elements of the gripping mechanism presented in this paper, the elements should be physically tested.

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Appendix A

Interviews

A.1 Interviewee A: 16.04.2018

NOTE TO READER: This interview was performed via e-mail

Q: I have a couple of questions regarding the specifications of the 3DBM: I would like to map commonalities between various cross-sections which are relevant today (max./min. outer dim., max./min. wall thickness, max. amount of chambers, etc.) – do you have any documentation regarding this which I may evaluate?

A: Typical cross-sections are maximum $100 \times 100mm$, with a cross-sectional area up to $1200mm^2$. Normally are these profiles one-chambered profiles, but two-chambered may occur (A-pillars, roof profiles etc.)

Q: I would like to map what cross-sections may be relevant for the future, do you have any assessment regarding this?

A: Yes, cross-sections with areas up to $1200mm^2$. Typically one-chambered profiles. Alloys 6060, 6063, 6005 and 6082.

Q: I want to map specifications for the machine (max. forces, cycle time, etc.), do you have do you have (NOTE TO READER: typographical error in the e-mail) made any changes regarding this in the new machine?

A: Maximum stretching force will be $20kN$.

Q: I would like to map what kind of force transmission between the extruded profile and the gripping mechanism are desirable (does everything have to be gripped with the same force uniformly, is it possibly sufficient to solely grip the corners or broad-sides, etc.)

A: Then it will be $20kN$ which will be limiting.

NOTE TO READER: The following was performed via e-mail a couple days later as a response to the previous e-mail.

Q: I reacted on the specifications you provided the other day, where you wrote that maximum stretching force will be $20kN$; in the documentation you have previously provided, it was stated that the 3DBM 2500-A had maximum forces of $200kN$ in each axis – will the power of the new machine only be a tenth of this, or have I misunderstood something?

A: Yes, you are correct. It is supposed to be $20tonnes$ in stretching ($200kN$)

A.2 Interviewee B: 15.05.2018

A: (Showing a CAD model of the gripping mechanism of the 3DBM 2500-A) On this gripping unit, we have the opportunity to have clamps on... four pieces. Gripping fingers or clamps, that you may have both upwards and downwards, and sideways. It may be nice to have the opportunity, but we do not use it... We have not used it on all of the products. Q: Sideways?

A: No, we have solely used upward and downwards, you may say.

(Interviewee explains the principle of the gripping mechanism of the 2DBM)

A: ...This works as well, because you are simply translating it straight in, the clamp descends, and then it stands like that retaining it all of the time – but then you have to keep on applying force. If anything happens so that anything fails, you have to apply force straight away. But, this one is faster, because you grip in one motion – translating it in, and grip simultaneously as you are translating.

Q: I have understood that when you are going to release it, then it releases a bit wrong, the 2DBM – is that because of this mechanism?

A: No. It is the same with this one.

Q: Oh, is it?

A: Yes, because it works pretty slowly. The thing is, it is a hydraulic cylinder, and it does not move fast, and the angle is small – so the relative movement up and down is not... it is not... Even though you move it $10mm$, it will only move $1mm$ upwards. Then it will release and scratch the aluminum. That is... That is a challenge anyways, to get it to move fast enough. Ideally, it should just *makes a snapping sound with the mouth* like that.

(Interviewee explains aspects of the 3DBM 2500-A)

A: With hydraulics, you can make it pretty compact and still get a lot of force.

Q: Yes, at the expense of accuracy?

A: Yes, but you don't need accuracy when you are going to grip, because it is simply to get enough force. It will just stop the force. The upside of hydraulics is that when the pressure is on – if something happens so the system yields – it will apply more force all the time. But if you are going to control it electrically, you have to control it by the force – that it always should apply a set amount of force all the time. If thinning occurs – you know – so that the material becomes thinner, you have to keep on applying. You can't just move it to position and let it stand like that.

A.3 Interviewee E: 28.05.2018

A PhD student at NTNU provided a framework for performing Abaqus parameter studies. This framework is presented in Appendix D.

A.4 Interviewee B: 07.06.2018

An interview with an employee at the automotive parts manufacturer was arranged in order to communicate sets and gain feedback. The sets communicated was the ”self-locking” clamps, and the ”fluid” and ”stacked elements” mandrels, all of which were communicated by the use of crude sketches, as presented in Fig. A.1. The employee responded positively to the self-locking clamp principle relying on separating the mandrel and clamp, and proposed a novel clamp mechanism: the knee joint. The knee joint concept was communicated visually, as resented in Fig. A.2. Further, the employee argued that fluid mandrels as mandrels counter-acting the clamps could be deemed infeasible, but informed that the fluid mandrel principles could be employed as an additional to mechanical mandrels to reduce cross-sectional deformations: the fluid mandrel principle relying on internal pressure was employed elsewhere in the forming industry, but was too time-consuming and fragile for mass-production; the fluid mandrel principle relying on inflatable balloon was previously tested in the R&D department with feasible results in reducing cross-sectional distortions. The ”stacked elements” mandrel was also previously tested in the R&D department with good results as a mandrel counter-acting the clamps.

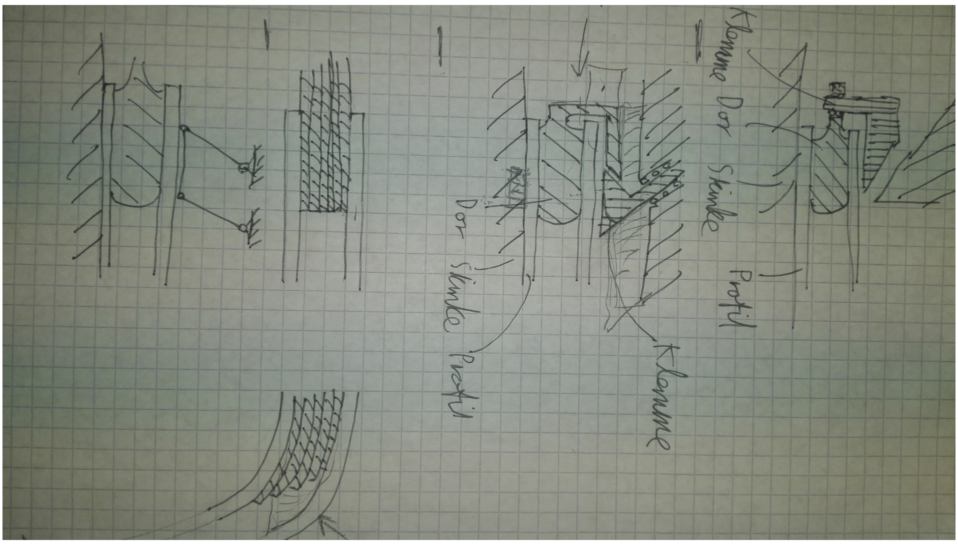


Figure A.1: Sketching during communication of sets

A.5 Interviewee A: 08.06.2018

Q: I have three questions. The first one is: the friction pattern is decided based on experience, if I have understood correctly?

A: That it is. That is correct.

Q: And on the 6XXX (alloy), it is the pyramid pattern? And on the 7XXX, it is the longitudinal surfaces?

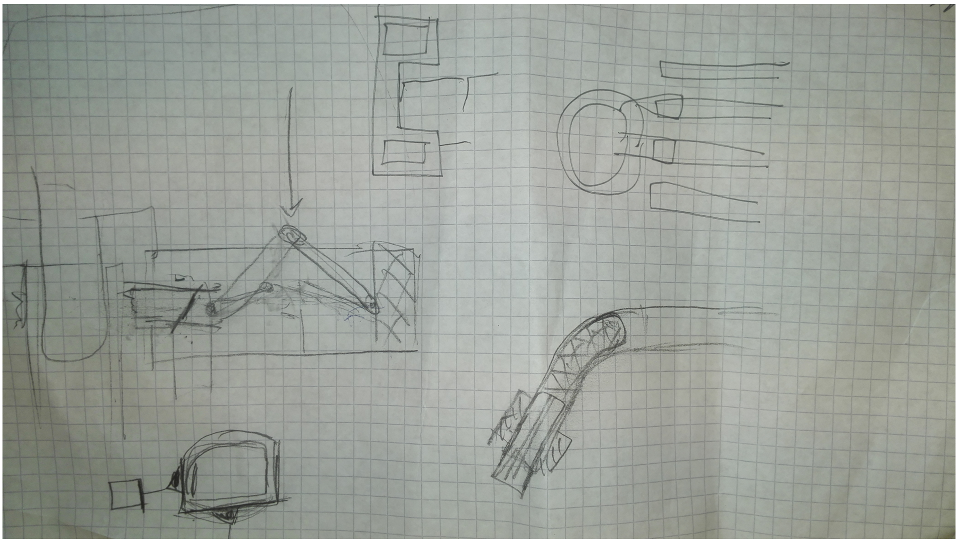


Figure A.2: Sketching during communication of sets

A: Yes, but it varies a bit. If you look here (shows a bent product with pyramid pattern markings), this is a 7XXX, so it is possible there as well. It's a little... There's no...

Q: So how do you decide? Is it during testing?

A: Often, we use the rule you state – but, if you have problems, you may try something different in order to make it stick.

Q: Ok. The second question was: I was inspecting your profiles downstairs (an in-house exhibition), and there was one, very rough pattern – not one of the two patterns I have seen before. Is that an earlier pattern?

A: Rough?

Q: I can show you a picture... (Shows picture of a component with rough friction pattern markings on mobile telephone)

A: Yes, that is just a really rough surface.

Q: Ok, is that something you have moved past?

A: No, sometimes that works as well. It depends on how much force you need for the stretching.

Q: Ok, so that is decided based on tests?

A: Yes, it is based on tests, some experience – there is actually no direct guidelines.

Q: I have seen that you have gripped this one (indicating a small, overhanging flange on a sketch), without a mandrel here (indicating the area underneath the overhanging flange). Is that because you allow deformation here, or because these walls are thick enough to withstand the grip...

A: That is because you can't reach this (area underneath the overhanging flange).

Q: Yes, but instead of just gripping here (indicating a surface aside from the overhanging flange), you have also gripped here (indicating overhanging flange) – is it heavy deformation at this point, or is it a judgement that the walls are thick enough to avoid heavy deformation?

A: Well, that looks a bit doubtful, if you ask me. I doubt the one who has set up this friction pattern have given it much of a thought. That is a little dangerous, because if you make contact, it may be locked, the one... I am sure there is only one which is effective, here. Either the one on top, or the one in the middle (indicating the surface area of the semi-hollow area between two overhanging flanges). It may be difficult to get them to work... To grip at the same time, you know? Because you will have variations here: sometimes, this is higher (indicating the overhanging flange), and this is lower (indicating the surface area of the semi-hollow area) – then it makes contact here (indicating the overhanging flange), and grips the most here... So it is very dependent on... So, that one may be a bit dangerous.

A.6 Interviewee B: 20.06.2018

Q: What are the constituents of a good grip? Do you desire to avoid yielding?

A: We want a friction. What we really want is to have some kind of pattern or geometry which makes it stick, and which makes the least amount of chipping. That is really important to us. To make a surface as big as possible have proven to effective, to make a structure – a pattern – that has a lot of surface, but that may result in chipping. That it can, because it is sharp surfaces, expensive to make, not least of all. Therefore, we have begun to look for alternatives. If you have enough forces to clamp this, you may manage it with big lines – like I've shown you before – which penetrate the material. But, like we've talked about earlier: we are not really sure what we want. We want to make friction without... First of all, we want to avoid the product looking ugly, that it is deep, that it is so deep craters that you can cut yourself. But it is also to avoid chippings, that is also important.

Q: On the gripping surface – I understand the importance of reaching yield in the points of penetration, of course – but do you try to avoid that more of the area reaches yield? Is that a criterion?

A: No, not really. What you are looking for – the sole criterion we have to check whether the gripping is working – is to check whether there has been a displacement or not. But, of course, if the material is so thin that you reach yield and everything continues to yield, then the gripping won't work. Because if you continue to apply forces when it yields, it will become thinner, and will fracture right in the front of where you are gripping – in the transition between the thick and thin part. Therefore, it is not as easy as to just apply forces until it really yields, because then you will get thinning, and then it won't work.

Q: So you want to avoid...

A: That the whole area reaches yield, that it reaches some kind of extrusion or... Cold flow forming. It will actually be some kind of cold flow forming. That you want to avoid. And that is not necessary either, this is – as you said – this is really complicated; to simulate a grip... forming simulation is not easy, because if you want to take all surfaces, it results in many elements – and small elements. So, I assume you are continuing (laughs), so you can take a more theoretical consideration of it.

Q: I got an answer, I was only wondering to what degree you wanted to yield, but you only want yield in the points of penetration.

A: It is to get... You want to reach yield at the tips in order to get a large surface, to get contact with a large surface. That's all. Then you have to stop. If you have a pattern, with really sharp pyramids, then they will penetrate easily. The area gets larger and larger, and in the end you reach maximum area; if you then continue, then it begins to cold flow form over the whole area, and the material will flow away. But it stops – when the area gets large – so it is always a balanced force you want to use when gripping. A thin profile, and an alloy with low strength, require less, and if you have a thick, massive, high alloy profile, then you need more force. The force has to be adjusted.

Q: If you have a surface like this (shows a drawing of a square surface, with clamps distributed in a zig-zag pattern), is it a problem to have gripping which begins at different points?

A: No, that is no problem. But the best thing would have been that you can not see on the product that it has been gripped. The customer would rather not have ugly markings, and – it may be visual as well – but if they are going to mount on the surface, so it has to be defined where you are allowed to have a pattern. So, the point is to have this (markings) as small as possible, actually.

(Interviewee explains coating for the components)

Q: Regarding the mandrel: are you relying on it to provide friction, or do you allow it – now I am specifically thinking of the 2DBM, where the mandrel is not free to follow – are you relying on it to provide friction, or do you allow it... Is it solely the clamps who...

A: Yes, external clamps. Well, we would have liked to... There have been made mandrels with clamps on the mandrels as well, but the problem is that there is a contradiction – contradiction (NOTE TO READER: in English), isn't that the English word? You would like friction on the mandrel as well, so you get a bigger surface – on the inside as well – but, the mandrel is entering a profile, and then we would like it to be polished, because it is narrow. Extruded profiles vary... Tolerances on an extruded profile are minimum and maximum, and you will get minimum profiles, and then we have to make the mandrel so that on a minimum profile, it is very tight. Or else it will be too much deformation, and you will get contact with the aluminum – and you are going to insert it perhaps $200mm$ inside a profile – and if you have clamps on it, you are just going to shred the aluminum and make a lot of chippings. Therefore, what is often done, is to make the mandrels completely smooth. So, you won't get any effect like extra friction or... But it has been performed on a few where the displacement is very short, then there have been made clamps on the mandrel. It's not that we don't want it – to make friction there as well – but, it is the contradiction; you are introducing other problems.

A.7 Interviewee B: 22.06.2018

An interview with an employee at the automotive parts manufacturer was arranged in order to pull design concepts. The interviewee claimed that the design of the friction surface pattern is based on experience. This is claimed to be dependent on the type of alloy, and the thickness of the profile. They claim the friction surface will be able to absorb the forces over a length of approximately $40mm$, but confess to having a bad experience in the development in these friction surface patterns, resulting in them being without a solid academic base. This was highlighted by one of my questions regarding whether the friction forces was increased due to an increase of contact area at penetration while the friction coefficient remained constant, an aspect they had not considered. The current friction patterns were pyramid shaped for the aluminum alloys of type AA6xxx, and line-shaped for aluminum alloys of type AA7xxx. The pyramid shape was reported to leave shavings, an unwanted feature, while the wave shape was claimed to increase the chance of fracture.

A.8 Interviewee A: 26.06.2018

Q: I have a couple of questions regarding strategy. Firstly: do you – in your process – aim towards having a lean process?

A: Yes, as lean as possible.

Q: Does that involve lean product development?

A: That depends on what you mean by lean product development. We try to strive for recycling... To have concept families that you reuse... If this is what you mean, this is the way we are working.

Q: Are you utilising set-based concurrent engineering?

A: No, we are not.

Q: Are there any specific reason for this?

A: Well, it's mainly that we are working the way we always have been working.

(Interviewer and interviewee discuss concepts)

A: You may weld two brackets onto it (the workpiece), with holes that you may insert a bolt through. That may be the cheapest of them all.

Q: What do you mean?

A: Well, if you have your profile, and weld two plates onto it, on both sides, with a hole through them. If you see it from above... (sketching while he talks) Here's the profile... And weld a plate onto it here...

Q: Straight onto the profile?

A: Straight onto the profile. Then you make a hole through it, and a bolt that you simply insert through. Then you cut off this afterwards – then you have a very cheap gripping mechanism. Then the gripping is simply – if you view it from the side – then you see the two plates and the profile here, welded, and holes (indicates on the sketch). That is the way we do it in the prototype workshop, if there is something we are going to make in small batches.

Q: Ok, are you?

A: Yes, we call it to "laske", we simply make profiles with a little extra length. You can't get anything cheaper than that – at least if you are going to make only five products, then you don't have to make... Then you make the plates, and weld them onto. The gripping may be positioned on the profile, or on the machine.

A.9 Interviewee A: 28.06.2018

Q: When you insert a profile into the machine, is the only possible way to do this descending from above, with the robots you have available? Or is it possible to insert it from the side?

A: It's surely possible to insert it from the side as well – the robot is flexible.

A.10 Interviewee D: 02.07.2018

A PhD student at NTNU stated that during aluminum bending, plastic mandrels are often utilised to support overhanging flanges if a high degree of tolerance accuracy is needed. Further, he stated that it is desirable to support throughout the entire cross-section, but that mandrels – for example of plastic – would be difficult to extract due to the deformation of the workpiece.

A.11 Interviewee C: 05.07.2018

Q: What would you say are the most critical factor?

A: With regards to gripping, the gripping process, or...

Q: Well, if you were to construct a good gripping mechanism, what would be the most important factor to focus on?

A: There's multiple important factors; one of them is that it is a safe process, right? And that there is as little maintenance as possible... That you have a high enough level of force – that you can grip hard enough, or with enough force.

Q: To grip it firmly?

A: Yes, to grip it firmly. And it is important what angle you are claming with.

(Talking about the knee joint concept, mostly with sketches)

A: The complexity in the entire unit with regard to assembly, disassembly, maintenance, and the like. If it is incredibly complex – let's say you spend half-a-day solely for disassembly, and two days for assembly – then that's a little silly. So, this (the knee joint concept) is driven hydraulically?

Q: Yes, so that it always is providing force.

A: And the rest are mechanical transmissions... Well, my experience is often like the ”Rema 1000”-principle ”the simplest thing is often the best” (NOTE TO READER: Rema 1000 is a colonial store in Norway, with this slogan), and this is related to the complexity.

(Talking about the complexity of the knee concept, and joints)

A: We used to had something (a joint) in the olden days which were called ”dog bone” – have you heard of it?

Q: No, how does it look?

A: The ”dog bone” is in principle an sphere, with force transmission in an angle.

(Interviewee explains the ”dog bone” joint with sketches)

A: But we have dropped this, as it is a little comp... Well, it's not exactly complex, but there is too many small parts. What we are using nowadays is simply wedge transmissions – simply a surface against surface – and on one of them, you have a ”T-track”

(Interviewee explains the ”T-track” joint with sketches)

(Discussion regarding concepts)

(Interviewer explains discrete clamping solution)

A: We usually make a friction surface which follows the surface of the profile. That is usually... You usually need it anyway, because profiles are seldom plane at the top – well, it exists – often, you have a flange, and it skews here (exemplifies through sketches), and one more pocket – then we simply make a friction surface which follows the shape. It is difficult to get... Well, what I worry regarding this (the discrete clamping), is that the gaps makes... The advantage with this – when you follow the shape – then you have grip. Contact all the way. If you you that principle (the discrete clamping), you loose contact underway. It may be sufficient – sometimes – but, generally, I think it is better... Are you supposed to have a friction surface which works on all profiles?

Q: Yes, as far as it goes. It should be more flexible .

A: Yes, ok... Then it becomes more complex, with these ones... Then you are thinking that one of them should be able to travel less deep that the other ones? And still have full force on all of them? Well... That'll be an interesting solution... We'll see... Well, that can be derived all the way to the needle principle, to have a bunch of needles which adjusts to the shape, but that is essentially the same thing we are using, if you have a look on the diamond pattern (NOTE TO READER: what is termed pyramid pattern in this paper), then you have... It is a similar principle, but you have a rigid shape. If you manage this – but it won't be a simple solution... The solution won't be simple. There is a contradiction: if it is going to be flexible, then it becomes very complicated. From my experience – eventually – you will not find – well, this is my experience at least – you won't find a solution which fits everything. Right? If you think about this profile (indicates on sketch). We have so many various profiles, that you will never get an universal friction surface. If you manage to create something like that, that adjusts... Good, but it will get very complicated – if you are going to change some parts, and perform maintenance, and the like... Of course, if you have a good solution, we will recognise it, it's not like I am excluding it, but... I do not think it will be easy... To have a completely flexible solution... I am afraid we're at least going to need – at least if you got a shape like this (indicates on sketch). And the same goes for the mandrel – we have double-chambered, triple-chambered, quadruple-chambered – the same goes for this: there are so many various shapes, sizes, and the like... You have to have an individual mandrel. Anyways. You can't have a mandrel which adjusts in size. Therefore, I am... I will be positively surprised if you find a solution which works on every shape.

A.12 Interviewee B: 11.07.2018

(Talking about standard parts for hydraulic and gas springs)

(Talking about joints)

Q: I heard from (NOTE TO READER: real name of Interviewee C was used) that you have a slideshow regarding joints – he talked about a T-track and the like, and explained them to me – and for the knee-joint, I heard that you used to utilise the dog bone joint.

A: Yes, we called it the dog bone.

Q: But it seemed to me that... Well, I solely need rotation... Not around the entire...

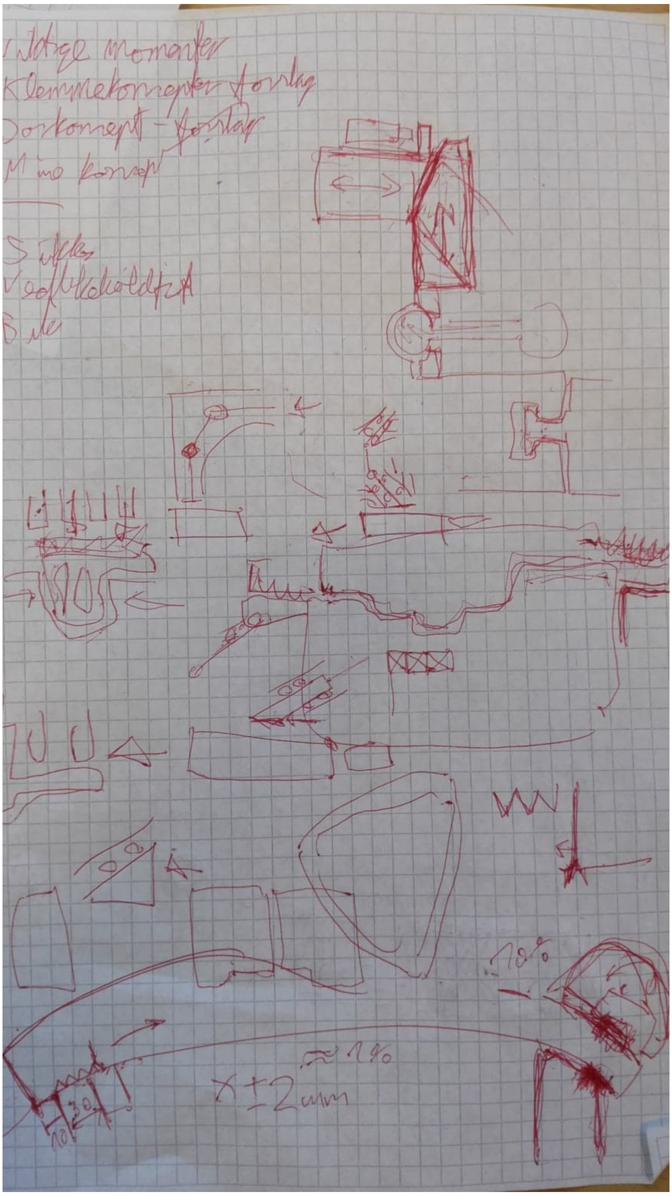


Figure A.3: Sketching during communication of sets

A: No, and then – dog bone is a sphere, and a sphere moves in all directions in space – and that was not utilised in that kind of systems. It was utilised on locking tools to transmit forces in an angle, and then the angle could move in three dimensional space. 3D in two directions – in two planes – and then one bolt is not sufficient because it will not work – that only covers one plane. Therefore, we utilised dog bone joint, and it was called dog

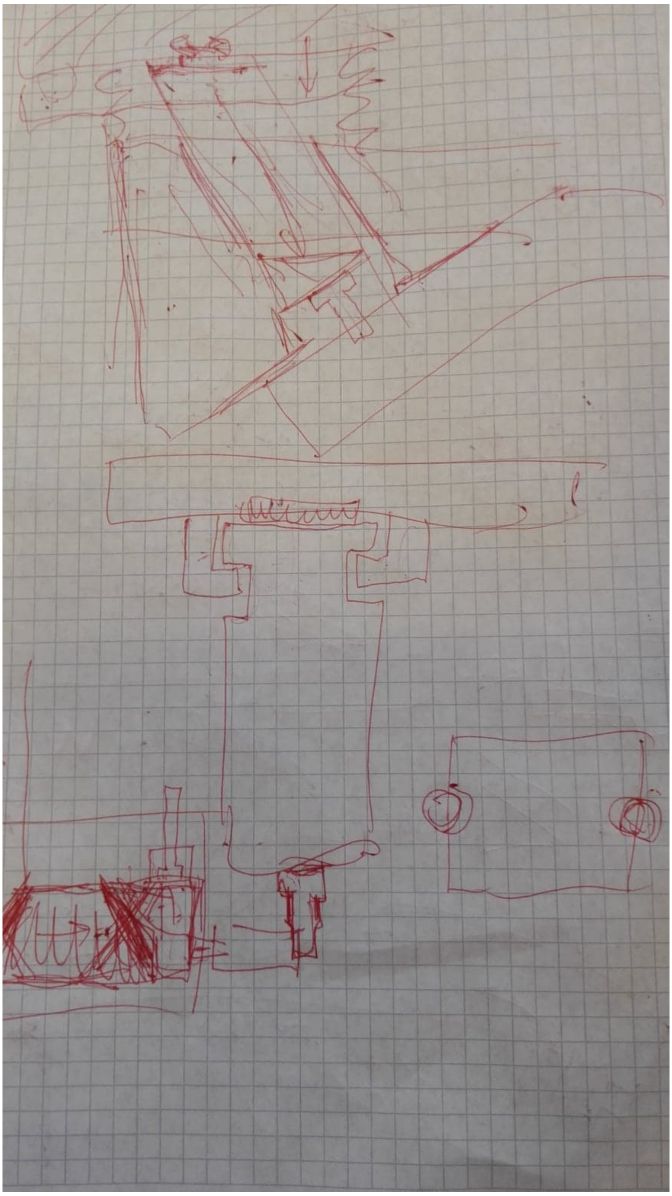


Figure A.4: Sketching during communication of sets

bone joints because there were a sphere in each extremity.

(Interviewee explains the dog bone joint)

A: So that was utilised, but in knee-joints bolts were utilised. Just bolts – circular bolts – because it is only in two dimensions. In 2d bending, you only bend in one plane.

(Talking about how the bolt joint could be utilised in the knee-joint concept)

Q: What about safety factors, are there any....

A: There are no safety factors *laughs*

Q: Here it will break! No, firstly, we utilise – in our tools, things move so slowly, so we talk about four to five hertz.... The hertz is four to five in a minute, right? Or something like that... Our pressing cycles, and the like... Perhaps fifteen seconds on one movement, so we don't utilise dynamic analyses, there's static we... We use safety factors based on static.... Static constructions... But often, we don't have space, so we have to be right at the limit in the load – perhaps right at what it can withstand – so sometimes it breaks. We don't have... It is almost like trial-and-error, sometimes we don't have the space, and we have to make in the best steel we know works and do it in the best possible manner – well, you have to have a clue, but how long it will hold, we can't exactly say. Sometimes we consciously make spare parts because we know it will break sooner or later, and then we exchange it, either sooner – well, preferably sooner. It is not possible to solve it in a different manner, but sometimes we have a factor of safety around two like it is in normal static calculations. It's not dynamic most of the things we do, there's no changing load. It moves so slow that the calculations considers it as static.

A.13 Interviewee B: 13.07.2018

(Talking about the continuous loose concept and the knee-joint concept)

A: What is best with regard to process is this one (indicates the knee-joint concept CAD model). If you take a look on the thing you move inwards, you have a friction surface here (indicates the clamp in the continuous loose concept CAD model), but this moves... The problem is that it moves inwards at the same time as it moves downwards, that means that if you have an enlarged part of the profile (sketches a segment of the profile enlarged) and a clamp (sketches a clamp) which moves inwards – it does not matter what the pattern is – and this sits in a system where this (the clamp) is driven in and moves downwards. There may still be an additional $10mm$ before it works, and from the first point of contact, it will dig into the product – and then some material will be scraped and lay in front of the friction pattern. That is the weakness of this solution. It is solvable with a transport – that you translate it inwards in a separate movement, and then the clamp could begin a downwards movement – so I think it is actually solvable.

(Talking about the movement of the continuous loose concept with indications to the CAD model)

Q: I understand, and I have given it some though, but I did not understand the difference between this solution and that of the 3DBM – that moves inwards at an angle as well?

(The interviewee explains visually that the housing of the 3DBM first translates inwards along the axis of d.o.f. 4, then the clamps are fixed along this axis, then the housing translates backwards along this axis, pushing the clamps downwards along the axis of d.o.f. 2)

(The interviewee explains visually how much movement the knee-joint clamps should have, and explains that it needs to begin at an angle where the force ratio is already large)

A: When this (the piston) is moved inwards, this (the clamps) travels very far. You can consider the force here, so it moves inwards with an angle like this (indicates visually a starting angle of the joint on the CAD model), $70°$ or something like that – then you have a little clearance – so it only moves the last $20°$. There is not much travel a thing like this needs – only $3 - 4mm$ – it only needs a clearance so it moves over the product.

A: If there is a product which stops here (indicates a small angle on the CAD model), it will not have enough force. It won't work. Therefore it will not... You have to adjust the height for it to be effective, so you don't necessitate too much force. The angle have to be small, so it will be forceful. It will not work if you have a high profile and one that is low, then it will only work for the one that is low. I think you should have to exchange. If you want to have a flexible solution, you exchange the lower part (of the clamp). You have a standard part, and if there is a height difference or something else, you have an exchangeable part. I am not sure if it is necessary with that many clamps... Three perhaps. That is enough.

(The interviewee explains that there are no need to clamp at a negative angle)

A: There is another thing... That you may utilise, which I haven't though of before... This (the housing and clamps) is two separate parts, which you can translate inwards and outwards pneumatically or electrically, separately from this (the clamping). It is only to position it.

(Interviewee sketches and explains)

A: If the housing translates at an $5°$ angle, so you have... You only translate the housing to this point (indicates a point along the track with some clearing to the end of the tracks), and the entire housing translates at an angle of $5°$ – even though there's a mandrel here, it should be possible to allow it to enter the profile – and then you stop at this position. Then, when the system clamps, you will have a self-locking mechanism. If you pull the product, it may slip a bit, but the entire housing will be dragged along – and it will grip tighter. There's no problem if this is exact, it may travel a millimetre or two, but you can't drive it to the end of the tracks. Then you might get the self-locking effect. You can check it out – $10°$ is too much, but a little may work.

A.14 Interviewee A: 20.07.2018

Q: I have a couple of questions regarding strategy, and a couple of questions regarding the model. Regarding strategy, I was wondering what you consider to be your competitive advantage. What the advantage of... Well, perhaps you talk a little bit about that?

A: The competitive advantage in the market? The automotive bumper market, you mean?

Q: Yes, why your methods – what you have to do with your methods to become competitive, and what makes your methods competitive.

A: What have made our methods competitive is that we have managed to remove variations from extrusions through forming – for example through stretch bending – so we are not required to calibrate and adjust the profile; they usually fit at once if they are supposed to be welded onto others. But if we are to survive in the future, we have to develop... Reduce the tool cost. The tools... More and more customers are not willing to pay so much for the tools any more.

Q: Ok, and what would you say are the advantage of extrusions compared to other methods?

A: That you can integrate functions that you cannot in a plate. You can have varying thickness, for example. If you are going to do that with plates, you have to weld it together, for example, with different plates or roller mill them in a particular way. And you may have hollow chambers without welding together plates. That's the advantage.

Q: Yes – you mentioned tool cost, what is your strategy to reduce the tool cost?

A: Yes, continuous improvement, but we also necessitate some radical steps if we are supposed to manage it – the 2DBM is actually radical compared to what we have had before. Then you move from a pressing tool to a much simpler setup, but with the same function. Well, partly: you can bend it, but you don't get to do anything else.

Q: Yes, I understand. Do you have any strategy regarding industry 4.0, how are you... Well, do you have a strategy regarding digitalisation in general?

A: Yes, there are strategies for this in (NOTE TO READER: Name of holding company). Not that I know the details of this. Of course, much of what we do could use the data from the line to a larger extent – to project how to form and... It is possible to do this.

(Talking about force ratio, and the travel length of the clamps)

Q: There's a problem with achieving enough travel length.

A: Yes, to open it up to insert the profile? How much vertical travel do you have now?

Q: It can be adjusted with the angle, but the problem is... And it can be adjusted with making the joint longer, but then it becomes incredibly long.

A: But as it stand now, how much do you have now? How much movement do you have now, vertically?

Q: Perhaps $5mm$.

A: That should be more than enough.

(Talking about travel length if the system are flexible and not product specific)

A: If you shift the entire thing (indicating a single clamp and track) in parallel – shifting the entire mechanism upwards and downwards – is that possible? That the next one is positioned...

Q: Yes, absolutely – if you allow it to be product specific.

A: Ok, because it is flexible now? Of course, if it is flexible, it needs to have certain limitations. It can't cover everything. In the worst case scenario, you can add a supporting piece (indicating on the bottom of the clamp)

Q: Yes, that is what I am thinking.

A: That have to be sufficient if you are only going to make a few.

Q: Yes, I think so as well.

A: Yes, I do not think that is any problem – it is much cheaper to machine such supporting pieces than to change the clamping every time.

Q: Ok, do you have any more thoughts... Well, do you think this is too complex?

A: It's not more complex than what it has been, is it? It is only two joints.

Q: Yes, but then there's three in parallel.

A: Yes, but there's not too much cost to produce something like that?

Q: No? Ok, good. The reason for having it in three clamps is that... If it was supposed to be product specific, it would be possible to have one clamp that had product specific clamping surface – but now I have separated it into three clamps so that is not product specific.

A: Yes, but why do you have three and not simply one large?

Q: Because... That is to make it flexible.

A: To manage variations transversely?

Q: Yes, to manage variations transversely, and to manage...

(Interviewer explains on the CAD model how the joints may manage workpieces with variating height)

Q: The height of the entire housing can be manipulated by – this (the tracks on the die) is by the way thought to be a part of the die – the tracks may be made lower to begin with. So even it the workpiece is small, there will not be any problem.

A: Well, normally I think I would have... What you could have done to make it more flexible, is to remove the lower tracks and fasten it with three-four strong screws from above. Then you could have inserted inserts in order to move the entire system upwards and downwards.

Q: Excuse me, could you explain that once more?

A: Here (indicates the tracks on the housing, interacting with the tracks on the die), you have tracks for fastening. If you removed this, and simply had a screw – four screws, for example – down here. Then you could adjust it even more. You could have inserted some thick inserts, or something like that, if you need more space.

Q: Ok, I'll think about that. The reason I have done it like this (indicates the tracks between the housing and the die) is that I have assumed that the die is product specific anyways, so you could simply machine the tracks lower.

A: Yes, I was thinking that if you were to use the die for multiple products, you could have a steel frame, and you could simply insert a wooden...

Q: I think I understand... Do you mean that you insert a small...

A: What I mean is that if it's positioned like this...

(Interviewee explains with sketches)

A: Then you could have a steel die that is only the frame, and insert wooden dies into it. Then the system could be very flexible.

Q: Bending against a wooden die?

A: Yes, we do it like that if we're only going to make five products. A die of wood instead of steel. Let's say some students are going to make some car parts for the...

Q: Revolve?

A: Yes, and they only need two parts, but perhaps needs a couple to try it out. Then they could use a wooden die, it costs next to nothing – five to ten thousand NOK. Then they could insert it straight into the frame, and bend it. Then you can have the house (explains with sketches), and you have any kind of bending shape, then you could insert wooden pieces into it with the bending shape you need – in plastic or wood, or something like that. Then there's just this wooden die, and you can go ahead – you can 3D print plastic inserts, and it will become immensely flexible.

Appendix B

Products

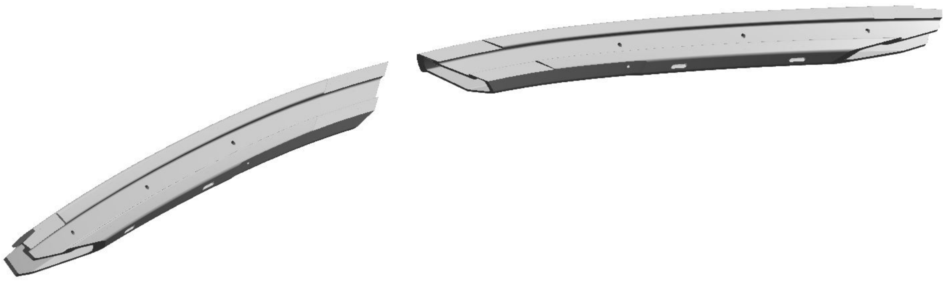


Figure B.1: The a-pillar frame as finished product

Figure B.2: Windshield frame

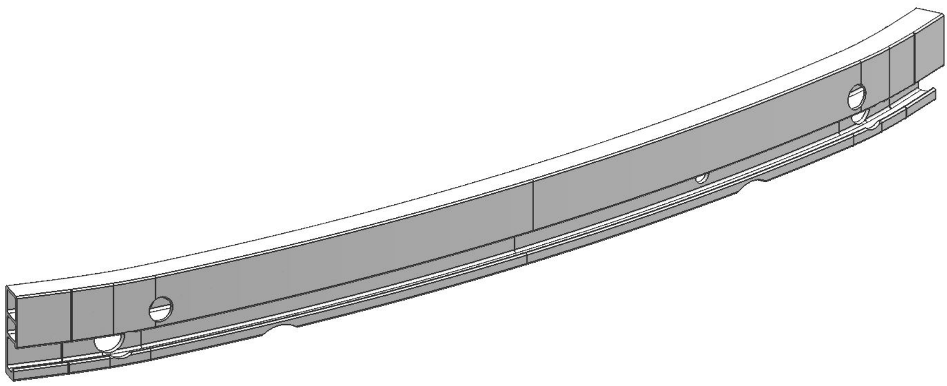


Figure B.3: Rear frame

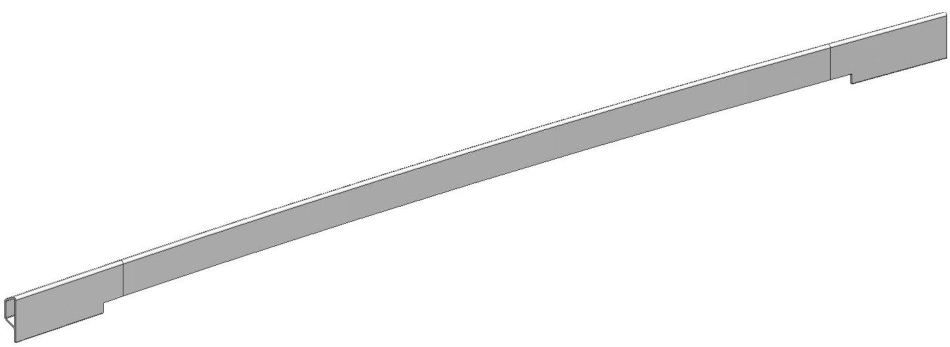


Figure B.4: The lower frame

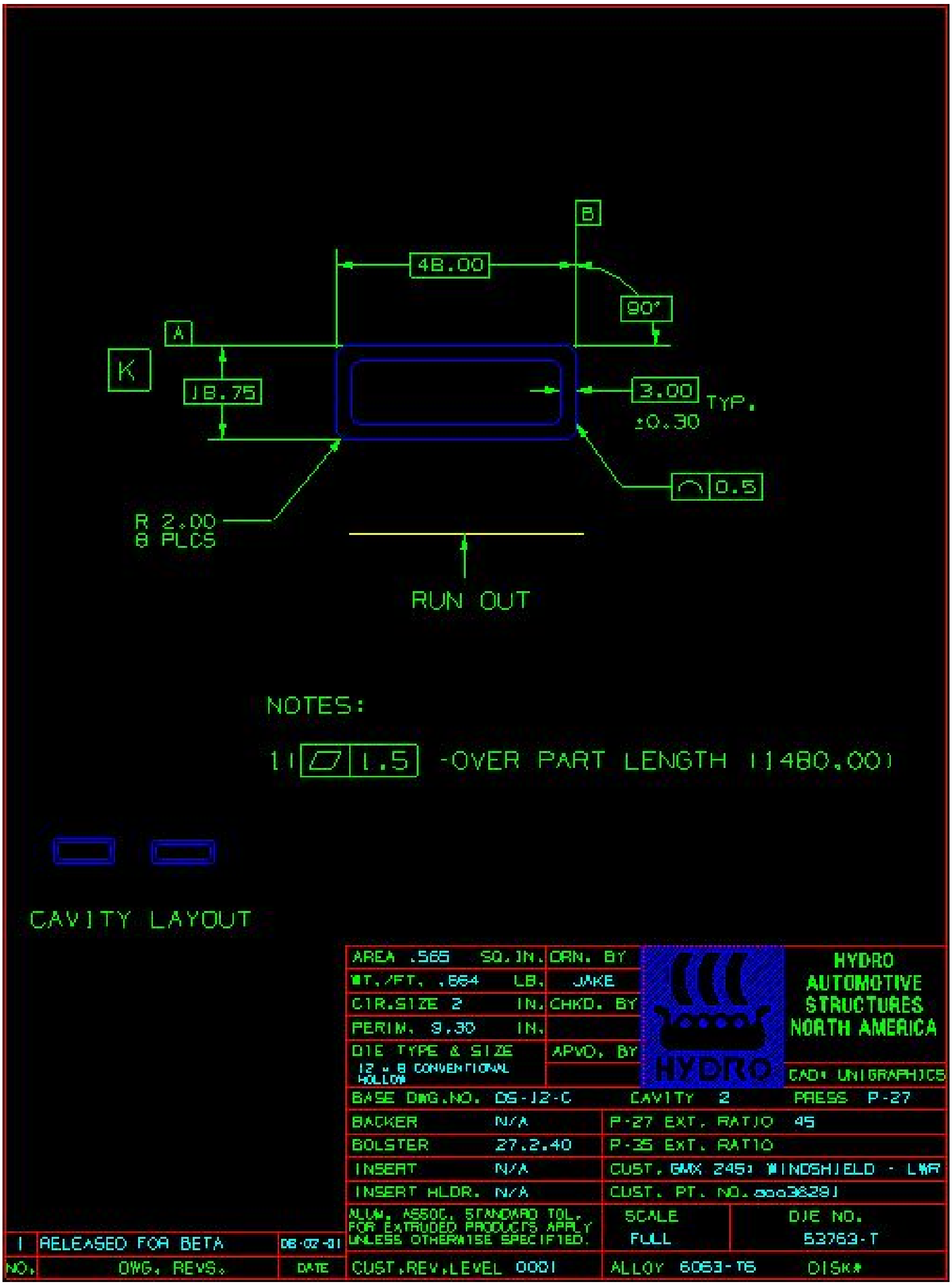


Figure B.5: Technical drawing of the windshield frame.

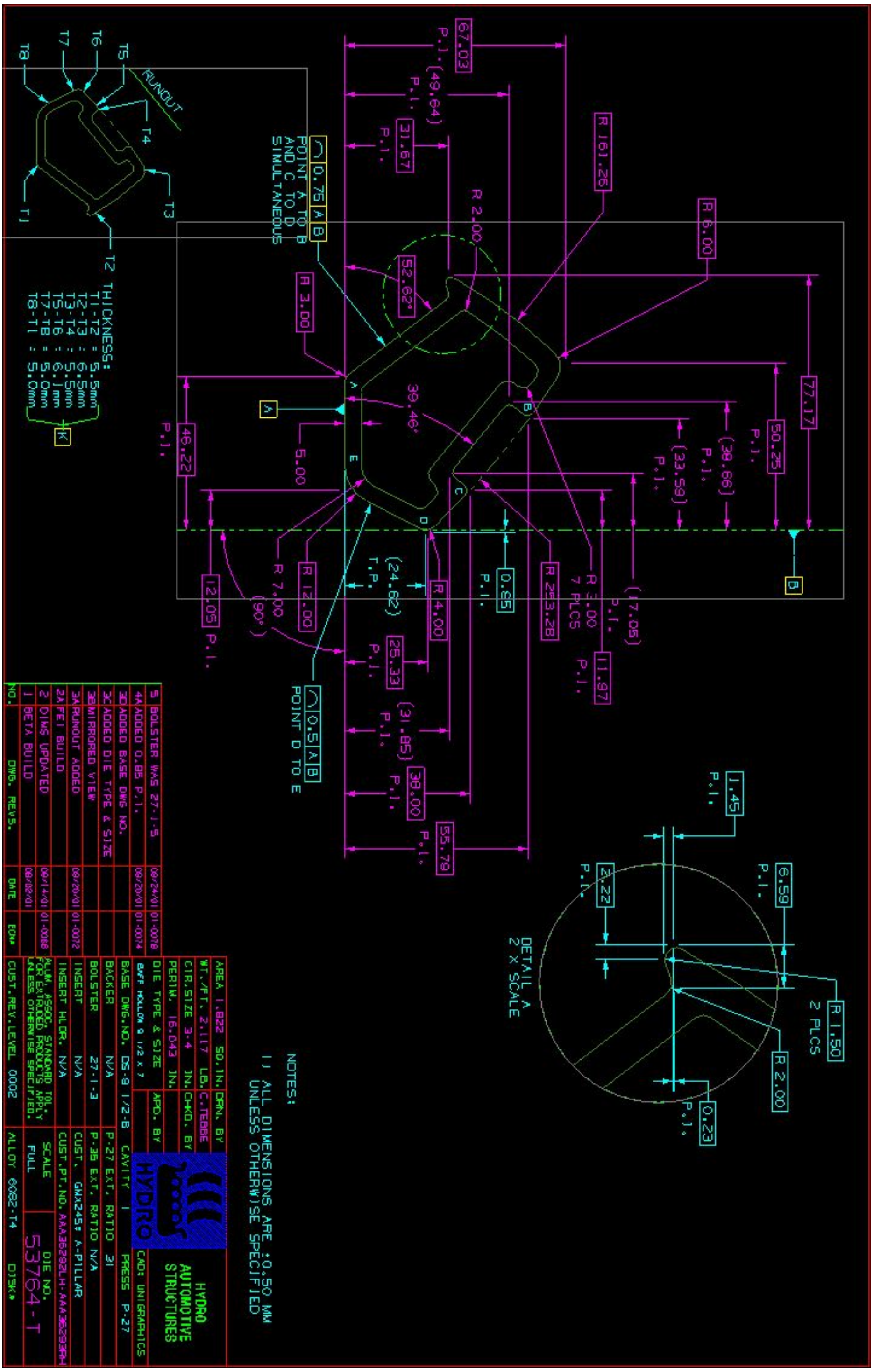


Figure B.6: Technical drawing of the A-pillar.

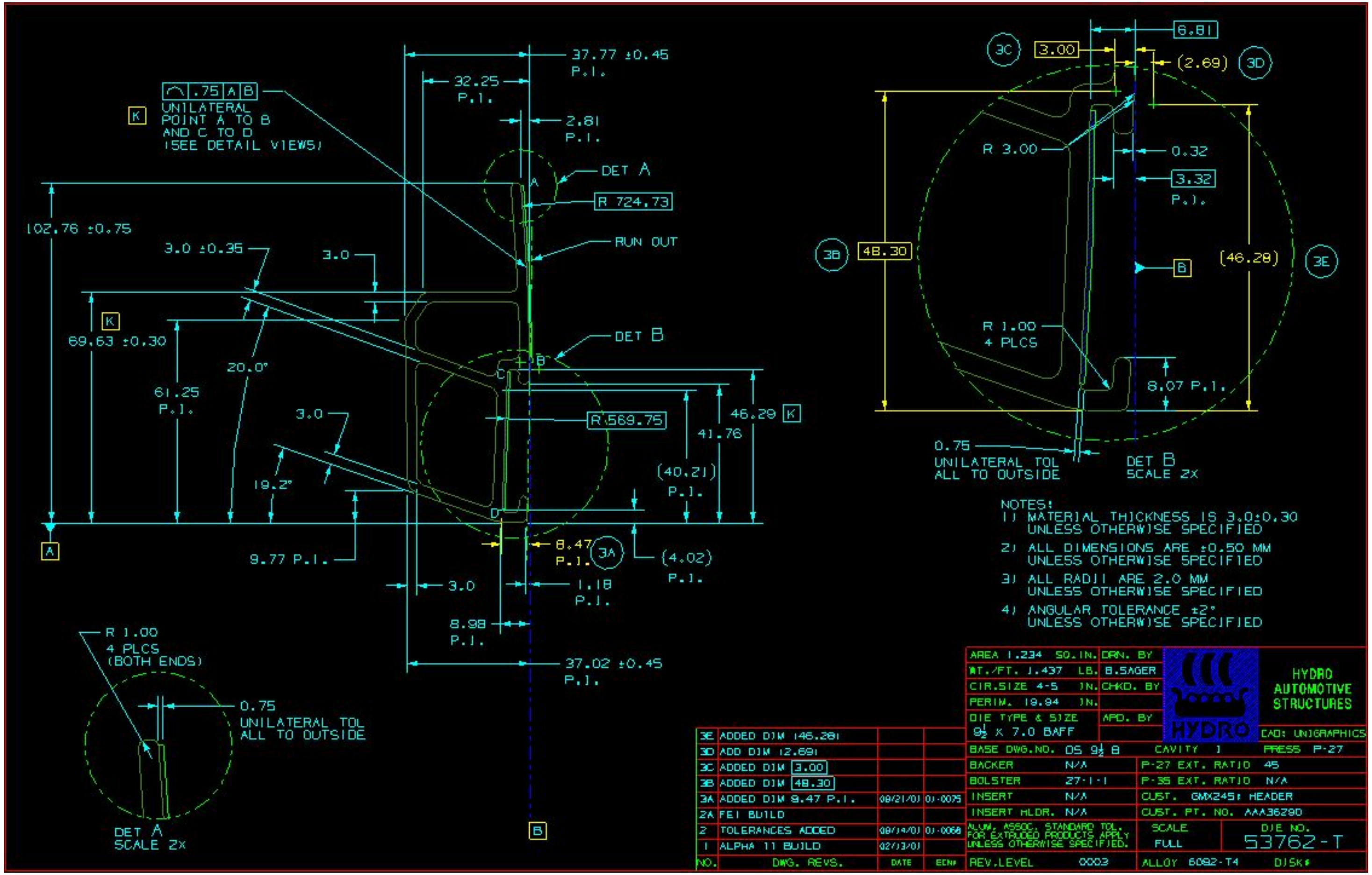


Figure B.7: Technical drawing of the header frame.

Appendix C

Profile feature terminology

The terminology of the profile features is indicated in Fig. C.1: feature 1 constituting a hollow cross-section is called a chamber, feature 2 separating chambers is a called a mid-wall, feature 3 is called a flange, feature 4 will in this paper be called overhanging flange (traditionally, all features ”sticking out” are called flanges), feature 5, a side enclosed by overhanging-flanges constitutes a semi-hollow cross-section. A profile with no chambers are called a solid cross-section, and a profile with two or more chambers are called a double-chambered cross-section, triple-chambered cross-section, etc.

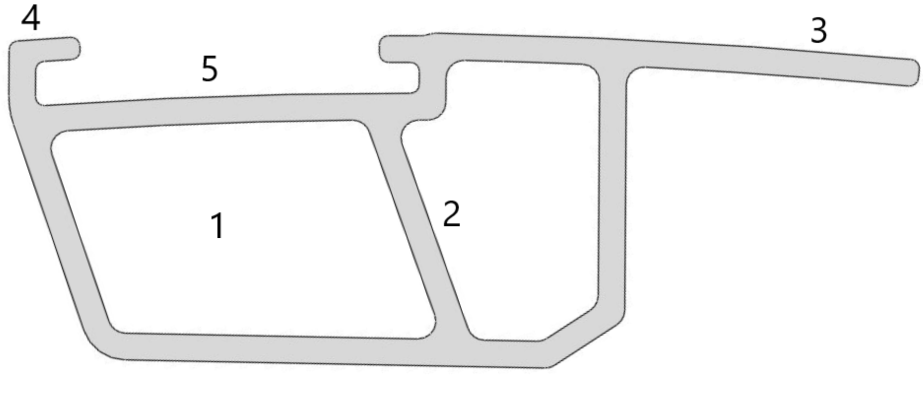


Figure C.1: Terminology of profile features

Appendix D

Abaqus parameter study framework

```
from abaqusConstants import *
from abaqus import *
#from abaqusConstants import MISES, UNIFORM, SINGLE, OFF, ODB, ANALYSIS,
DEFAULT, PERCENTAGE # etc.
from odbAccess import openOdb
import numpy as np

    def run():
values1 = [1, 2]
values2 = [1]
modelname = 'Model-1'
outdata = np.ndarray((len(values1)*len(values2), 4))
mdb = openMdb('ParameterTest.cae') #"Model file name (.cae)"

    i = 0
for val1 in values1:
for val2 in values2:

    print("Setting val1 to" + str(val1))
mdb.models['Model-1'].Pressure(amplitude=UNSET, createStepName='LastStep',
distributionType=UNIFORM, field='',
magnitude=val1, name='TrykkLoad',
region= mdb.models['Model-1'].rootAssembly.surfaces['GripebakkeTrykkOversideSurface'])

    print("Setting val2 to "+ str(val2))
mdb.models['Model-1'].boundaryConditions['GripebakkeDisplacement'].setValuesInStep(
amplitude='SmoothAmplitude',
stepName='LastStep', u3=val2)
# Example. Set displacement in y-direction to val1
```

```
#print(”Setting val1 to” + str(val1))
#mdb.models[modelname].boundaryConditions['GripebakkeDisplacement'].setValues(u3=val1)
# Example. Set load cf1 (concentrated force in x-direction) to val2
#print(”Setting val2 to ”+ str(val2))
#mdb.models[modelname].loads['TrykkLoad'].setValues( # cf1=val2, distributionType=UNIFORM,
field=”)

    jobname = modelname
job = mdb.Job(atTime=None,
contactPrint=OFF, description=”,
echoPrint=OFF,
explicitPrecision=SINGLE,
getMemoryFromAnalysis=True,
historyPrint=OFF,
memory=90, memoryUnits=PERCENTAGE,
model=modelname,
modelPrint=OFF,
multiprocessingMode=DEFAULT,
name=jobname,
nodalOutputPrecision=SINGLE,
numCpus=4, numDomains=4, numGPUs=0, queue=None
, resultsFormat=ODB, scratch=”,
type=ANALYSIS, userSubroutine=”,
waitHours=0, waitMinutes=0)

    job.submit(consistencyChecking=OFF)
print(”Submitted job, waiting for
completion...”)
job.waitForCompletion()

    odb = openOdb(jobname + ”.odb”,
readOnly=True)
nodeset = odb.rootAssembly.nodeSets['OutputNodeSet2']
rf1 = odb.steps['Navn paa steg'].frames[-1].fieldOutputs['RF'].getSubset(region=nodeset).values[0].data[0]
rf2 = odb.steps['Navn paa steg'].frames[-1].fieldOutputs['RF'].getSubset(region=nodeset).values[0].data[1]
outdata[i][0] = val1
outdata[i][1] = val2
outdata[i][2] = rf1
outdata[i][3] = rf2
i += 1
odb.close()
filename = ”Parameterstudie.csv”
np.savetxt(filename, outdata, delimiter=”,”)
print(”Parameterstudie completed!”)
```

Appendix E

Technical drawings of the system

E.1 Technical drawings of the house

The technical drawings of the solid house, the house insert, the house T-joint and the house back wall are presented in Fig. E.2, E.1, E.3 and E.4, respectively.

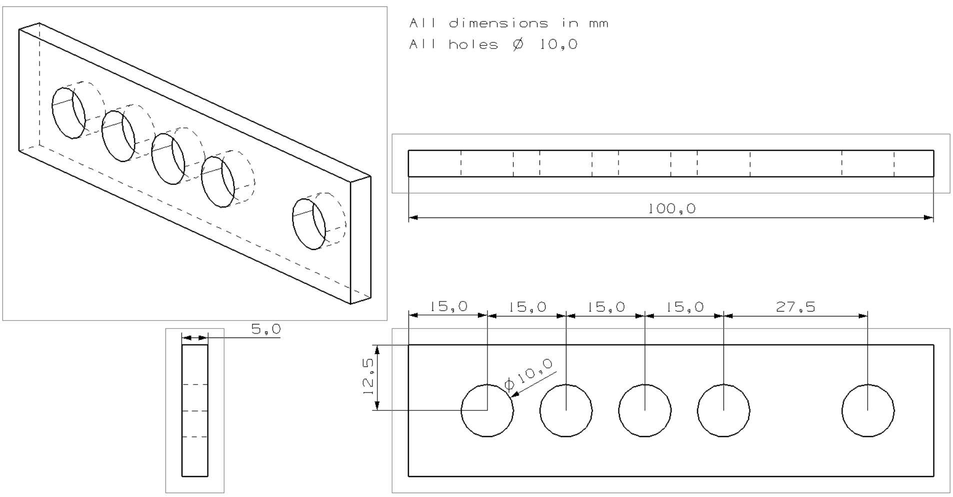


Figure E.1: Technical drawing of house insert

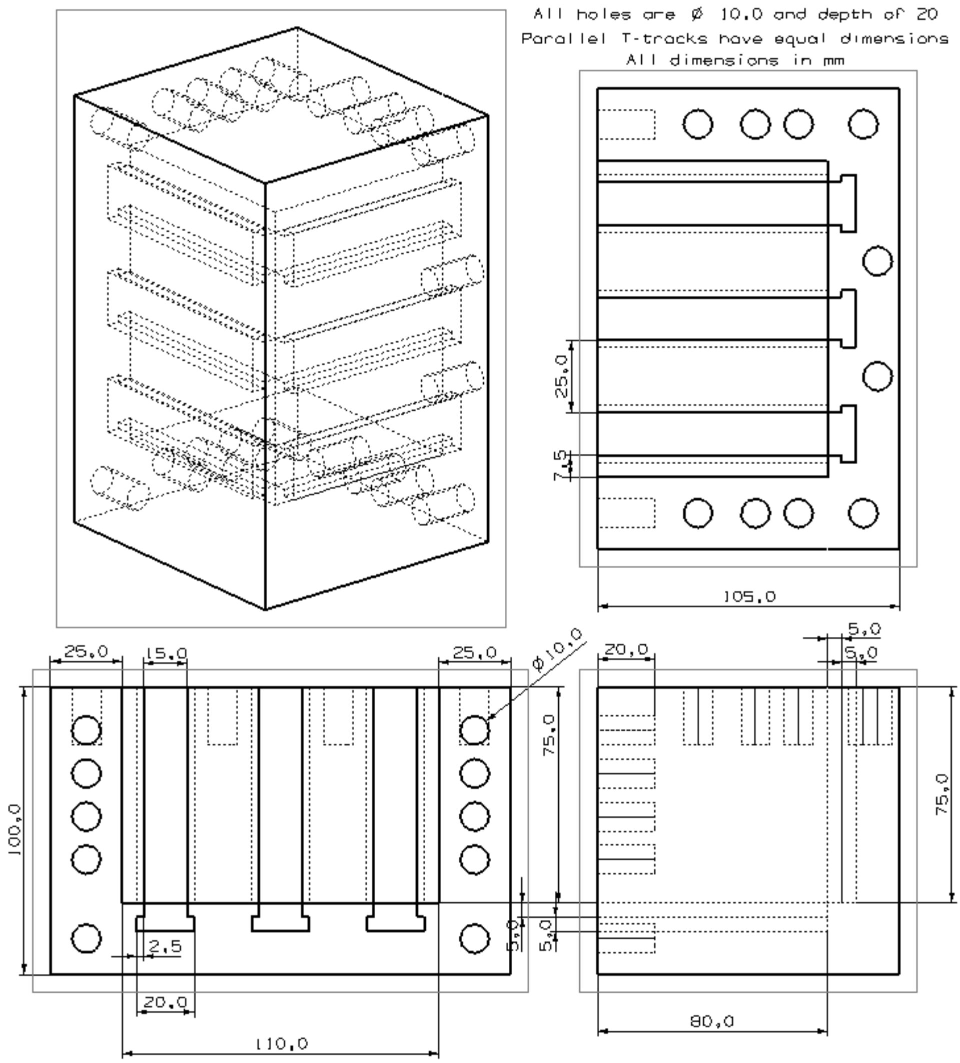


Figure E.2: Technical drawing of solid house

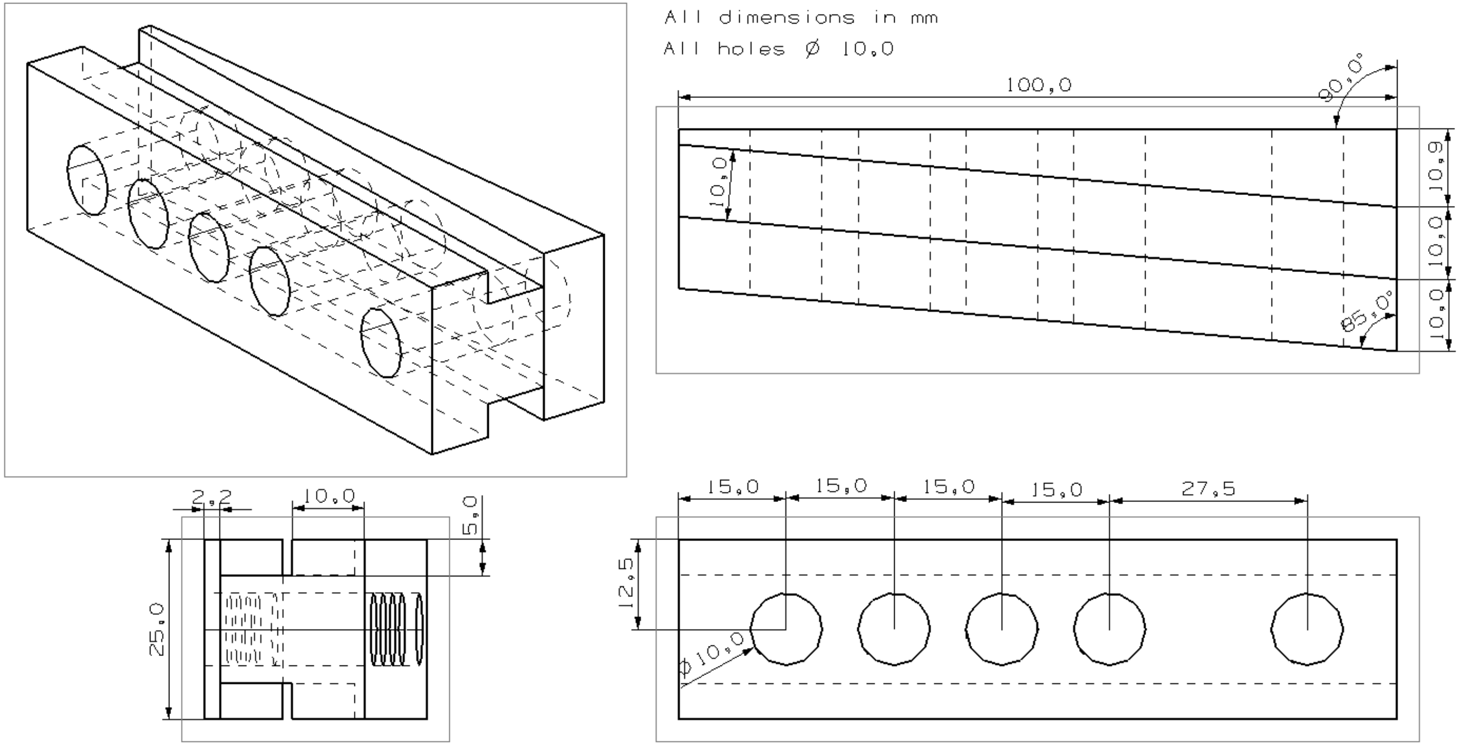


Figure E.3: Technical drawing of house T-joint

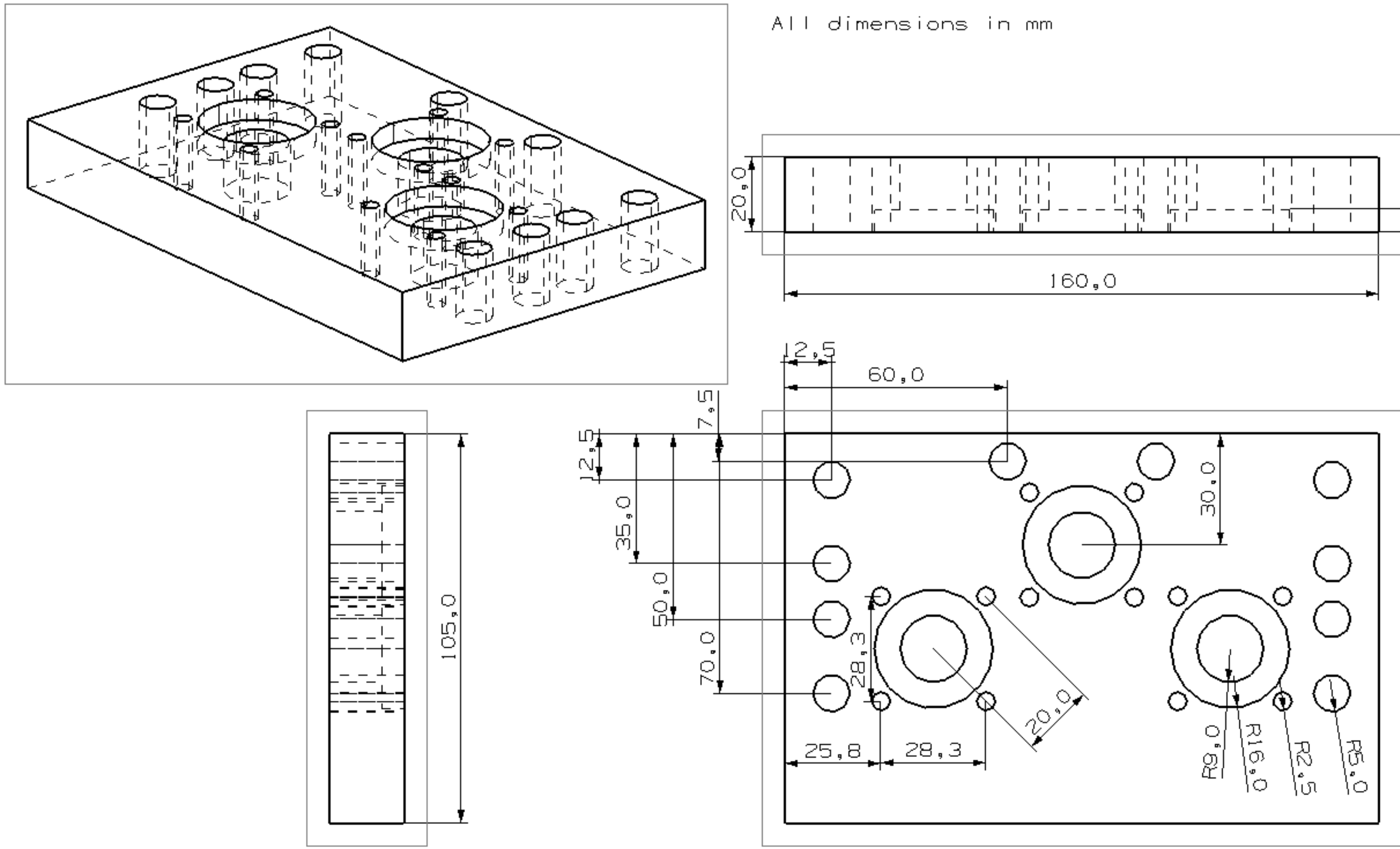


Figure E.4: Technical drawing of house back wall

E.2 Technical drawings of the knee-joint

The technical drawings of the knee-joint piston, the knee-joint joint and the knee-joint clamp are presented in Fig. E.5, E.6 and E.7, respectively.

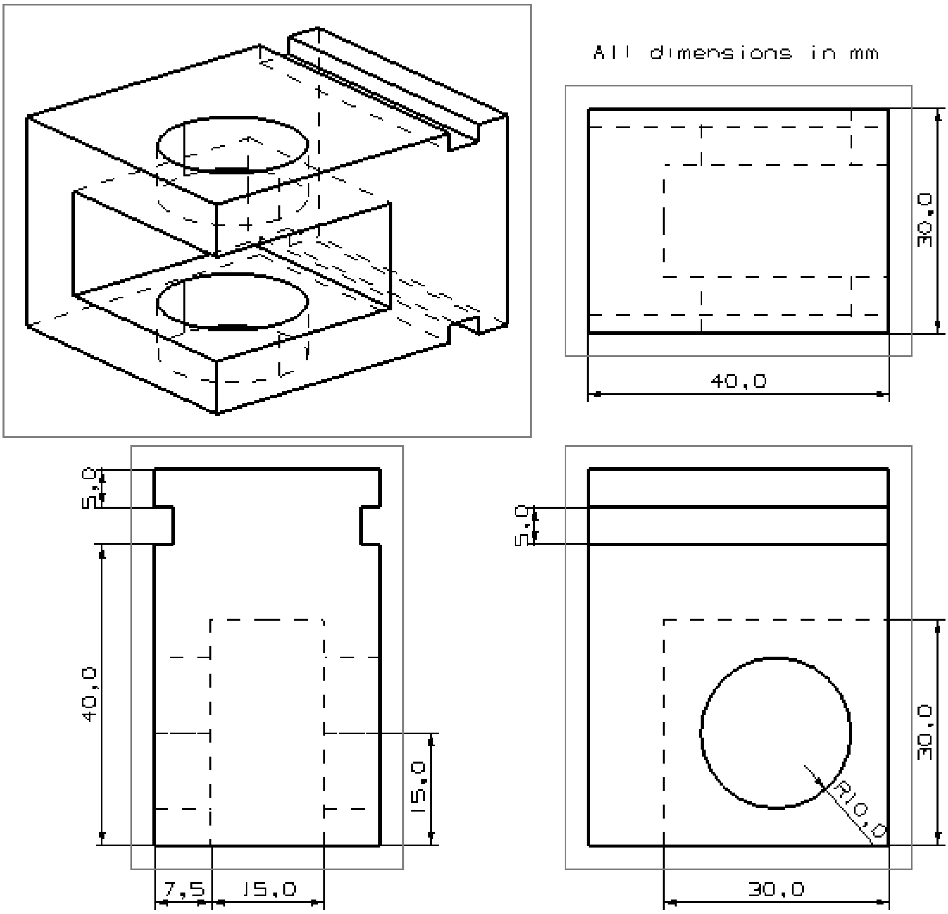


Figure E.5: Technical drawing of piston of knee-joint

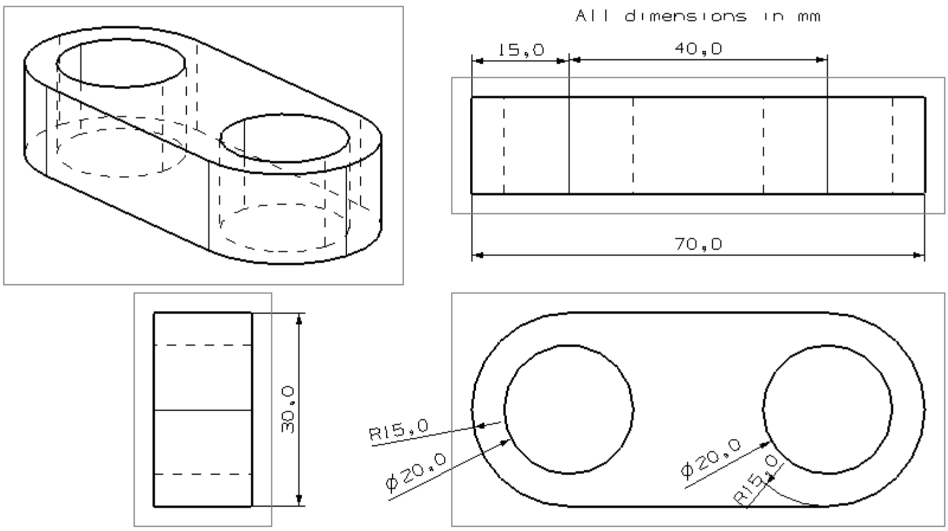


Figure E.6: Technical drawing of joint of knee-joint

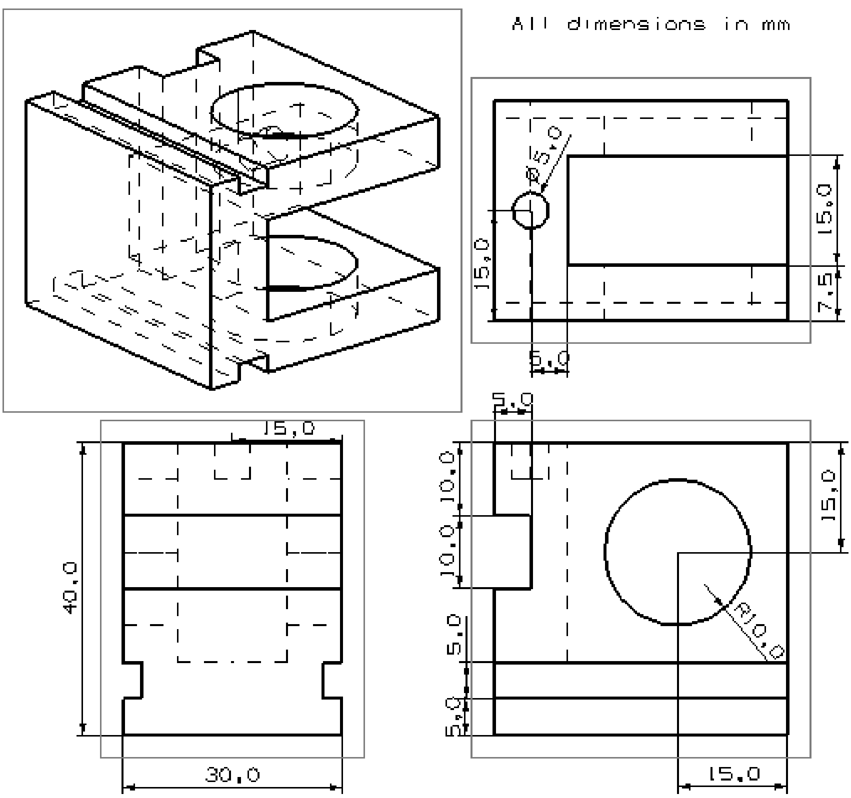


Figure E.7: Technical drawing of clamp of the knee-joint

E.3 Technical drawings of the clamp inserts

The technical drawings of the three clamp inserts (right, middle and left viewed towards the house back wall) are presented in Fig. E.8, E.9 and E.10, respectively. The product-specific parts of the clamp inserts are not given dimension, as it will vary with each product.

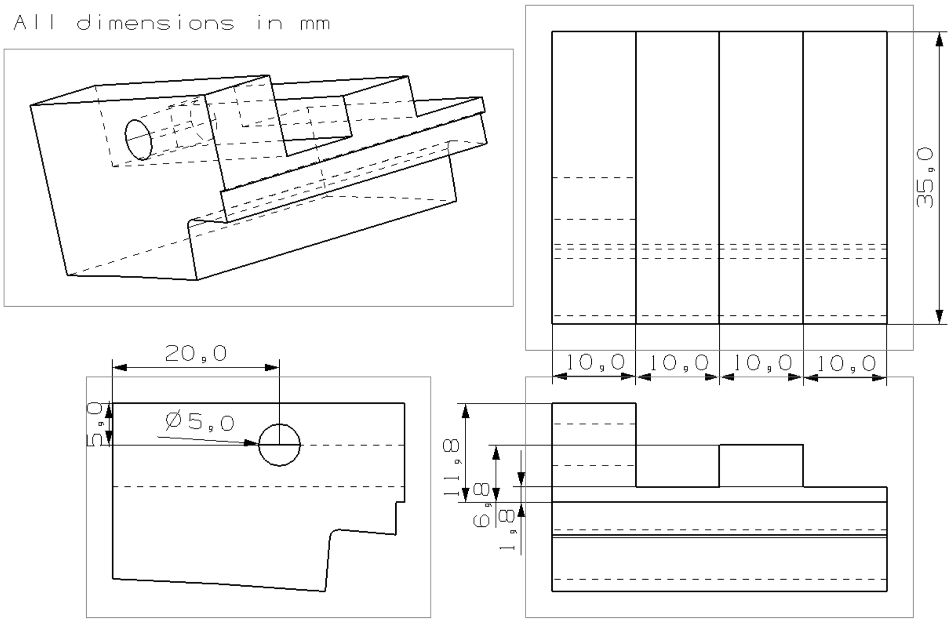


Figure E.8: Technical drawing of the right clamp insert (viewed towards the house back wall)

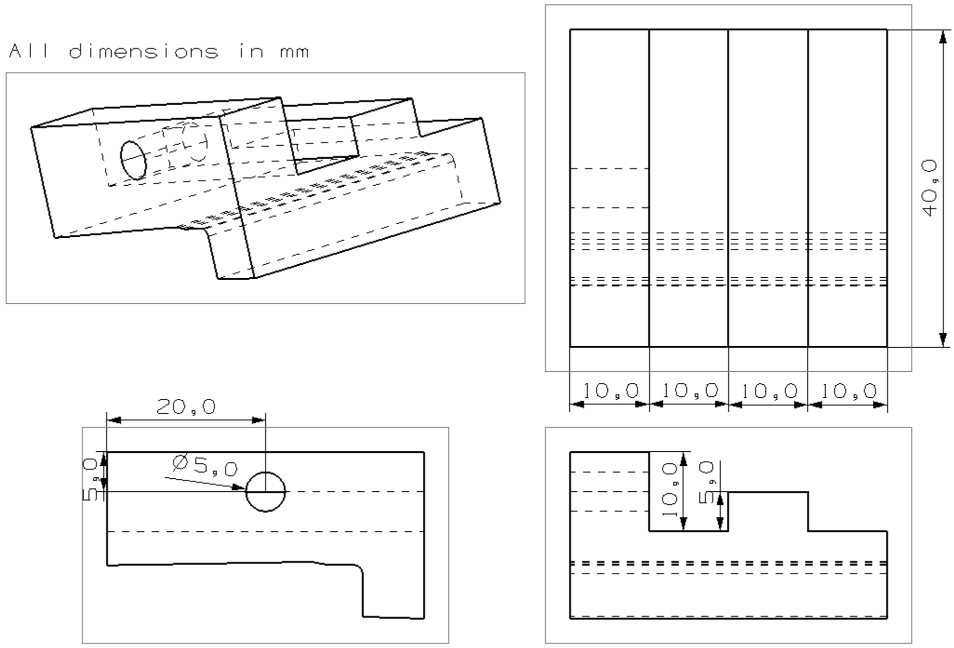


Figure E.9: Technical drawing of the middle clamp insert

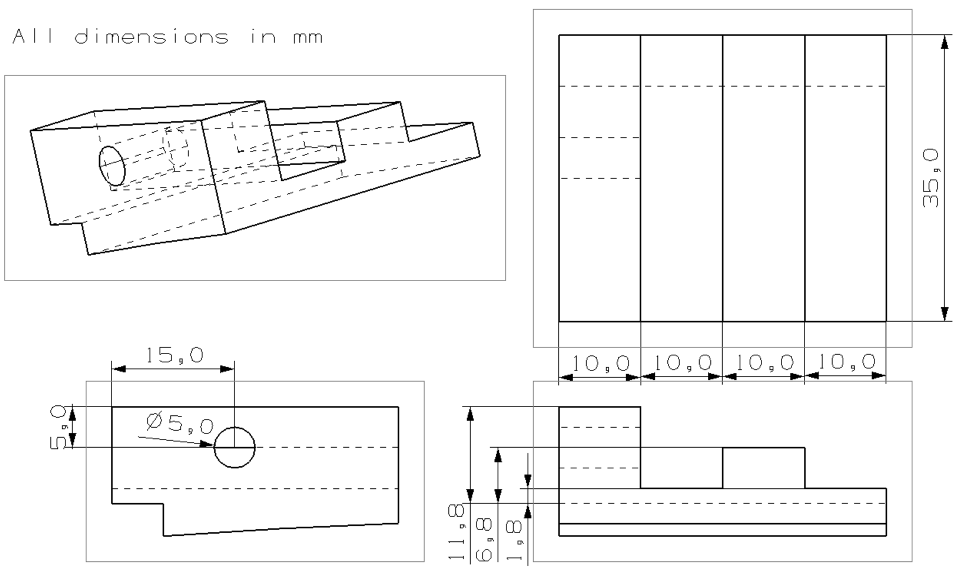


Figure E.10: Technical drawing of the left clamp insert (viewed towards the house back wall)

E.4 Technical drawings of the mandrel

The technical drawings of the mandrel is presented in Fig. E.11. The product-specific parts of the mandrel are not given dimension, as it will vary with each product.

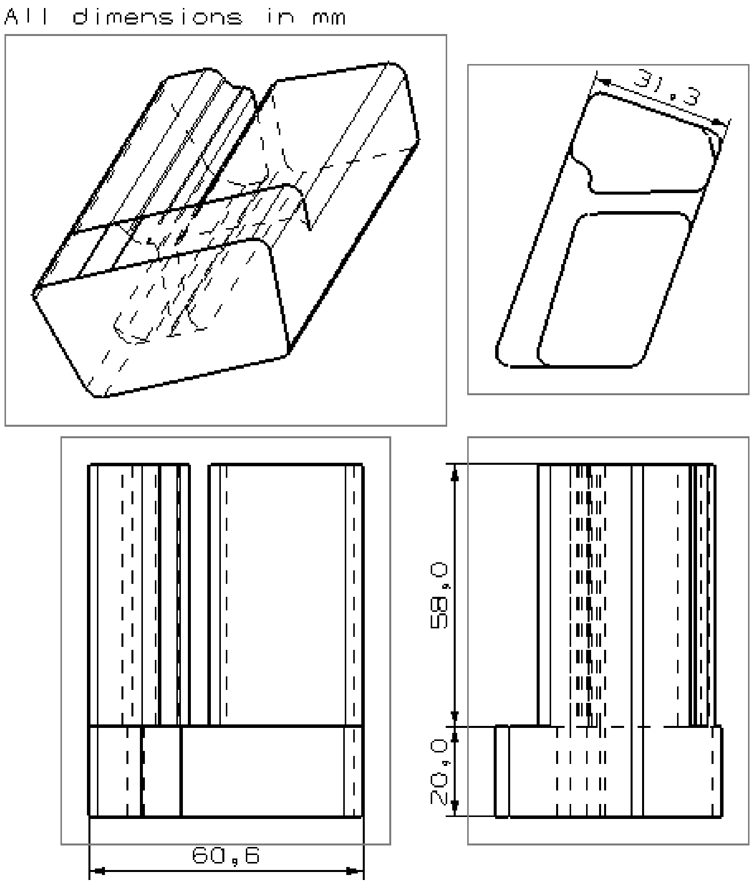


Figure E.11: Technical drawing of the mandrel

E.5 Technical drawings of the actuators

The technical drawing of the actuators is presented in Fig. E.12. This technical drawing has been downloaded from Bosch Rexroth's website.

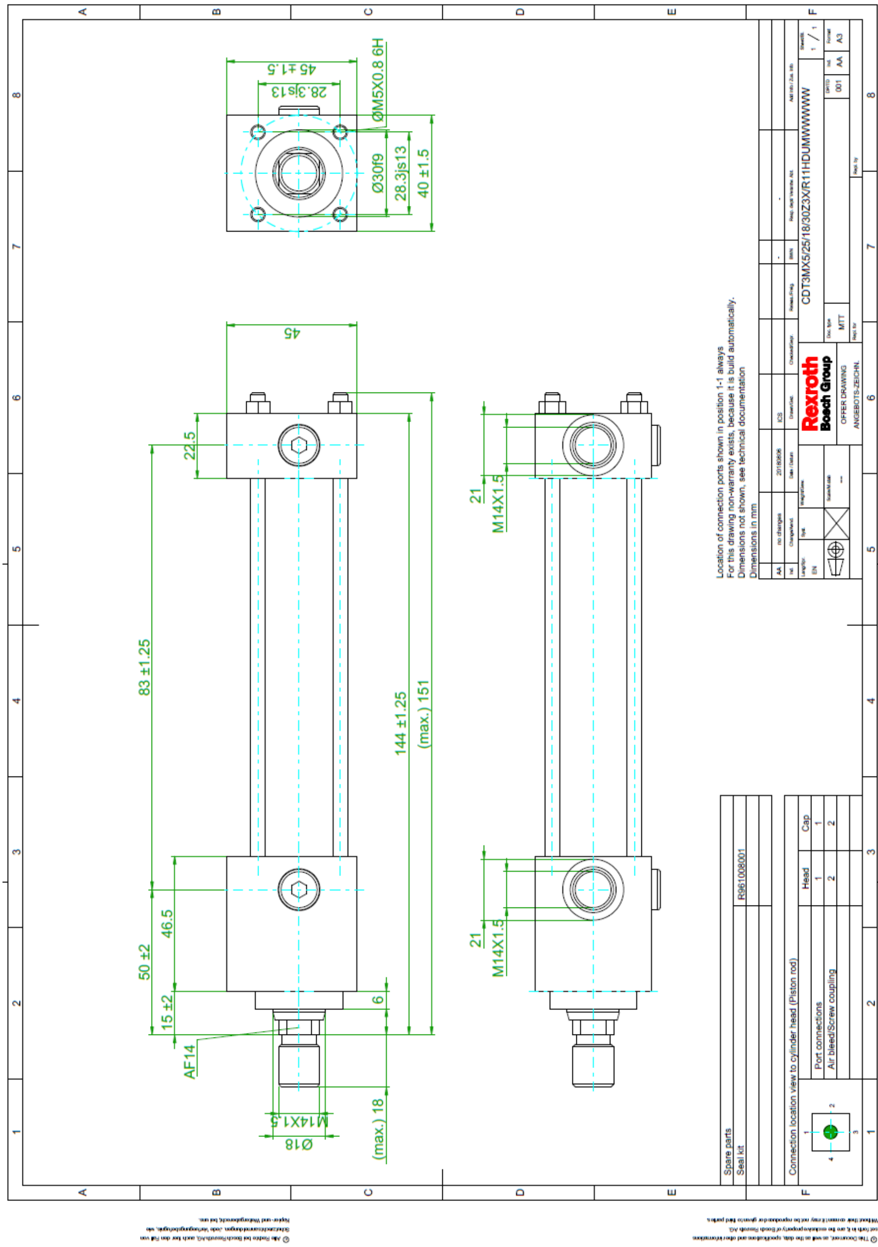


Figure E.12: Technical drawing of the actuator

Appendix F

CAE models

F.1 MPCs

The MPCs of the model are presented in Fig. F.1 and F.2. The MPC connections are graphically represented as centres of the yellow webs. The MPCs are described with the green text ”MPC Beam”. The MPC connections are graphically represented as stipled, blue lines.

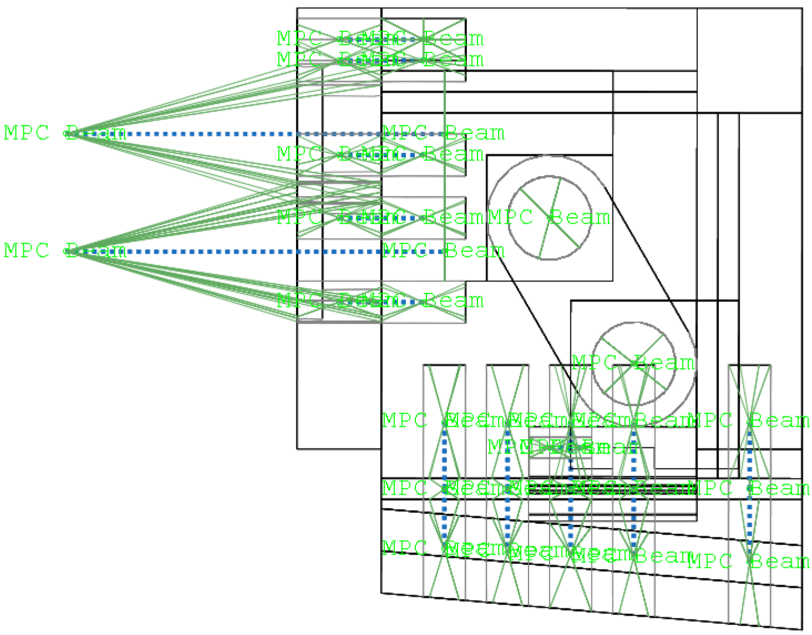


Figure F.1: MPCs of the model presented from the back

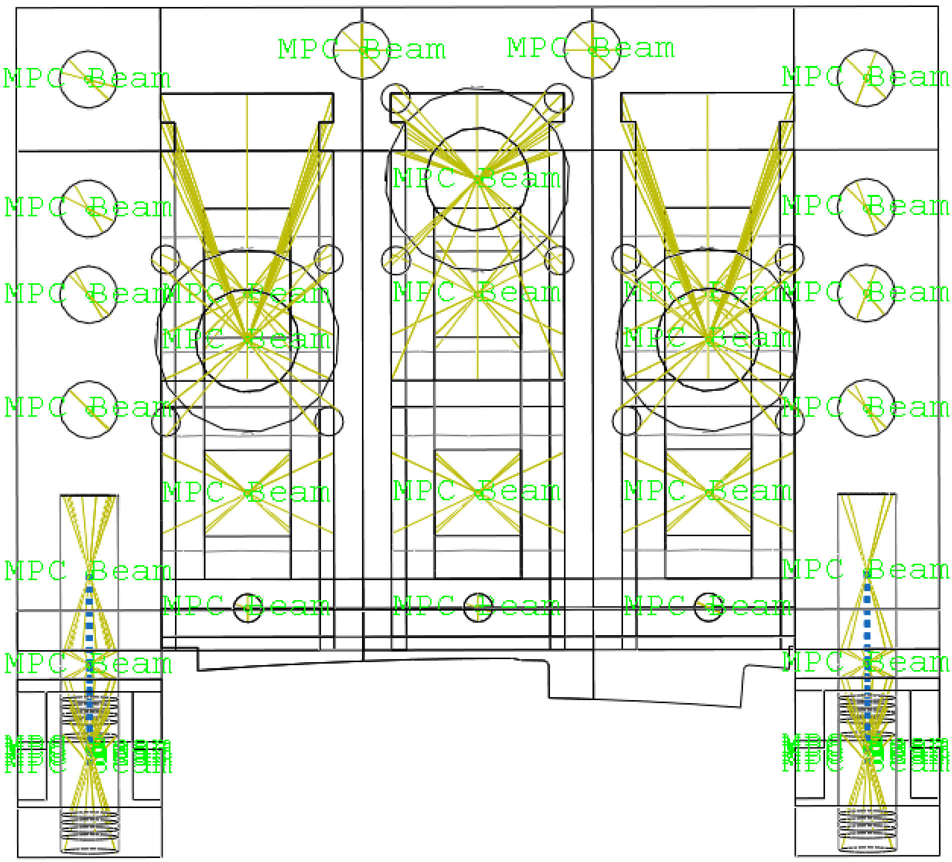
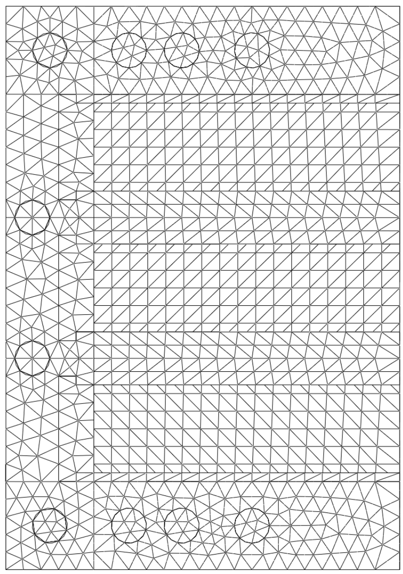


Figure F.2: MPCs of the model presented from the side

F.2 Mesh

The meshes of the solid house, the house back wall, the test product, the knee-joint's piston, joint and clamp, and the three clamp inserts (right, middle and left viewed towards the house back wall) are presented in Fig. F.3, F.4 and F.5, F.6, F.7, F.8, F.9, F.10 and F.11, respectively.



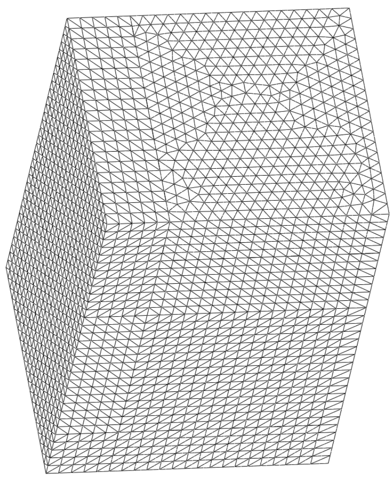


Figure F.3: Mesh of the solid house from an angle (left) and the back (right)

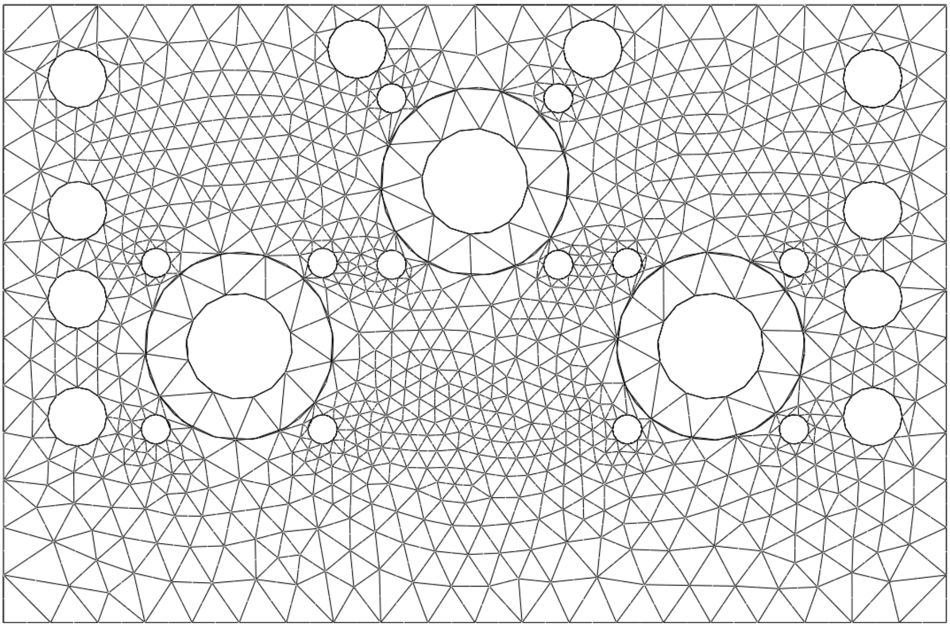


Figure F.4: Mesh of the house back wall

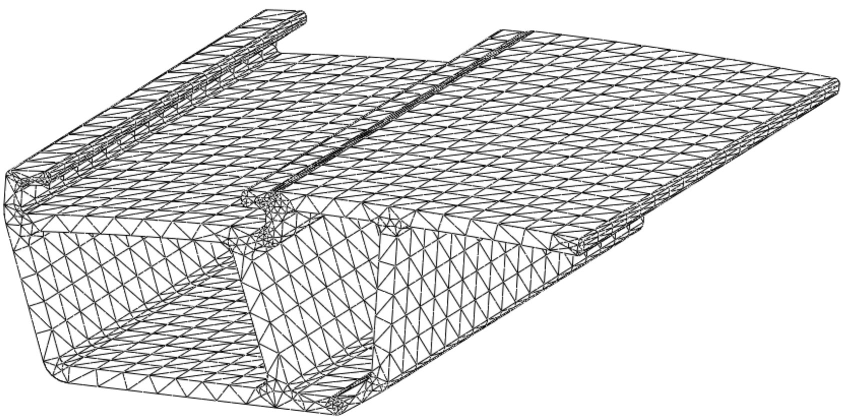


Figure F.5: Mesh of the test product

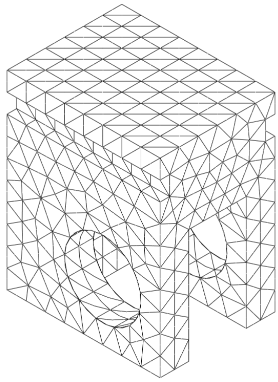


Figure F.6: Mesh of the knee-joint piston

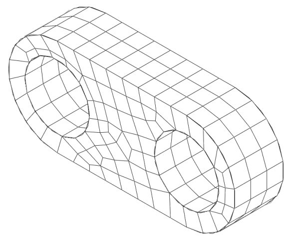


Figure F.7: Mesh of the knee-joint joint

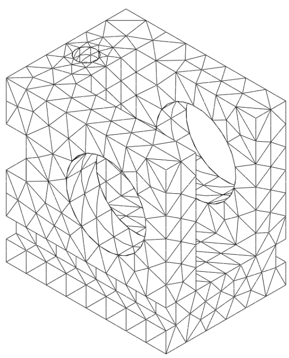


Figure F.8: Mesh of the knee-joint clamp

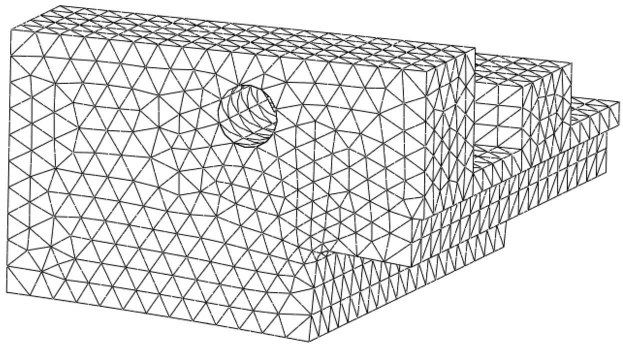


Figure F.9: Mesh of the right clamp insert (viewed towards the house back wall)

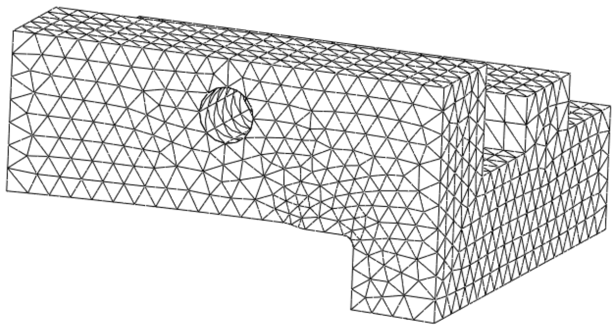


Figure F.10: Mesh of the middle clamp insert

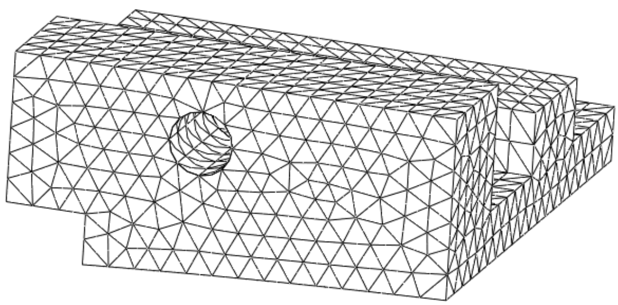


Figure F.11: Mesh of the left clamp insert (viewed towards the house back wall)

Appendix G

CAE analyses

G.1 Eigenfrequencies of the system

The frequency modes 2901.3 Hz and 5834.1 Hz are presented in Fig. G.1 and G.2. Presented with deformation scale 10.

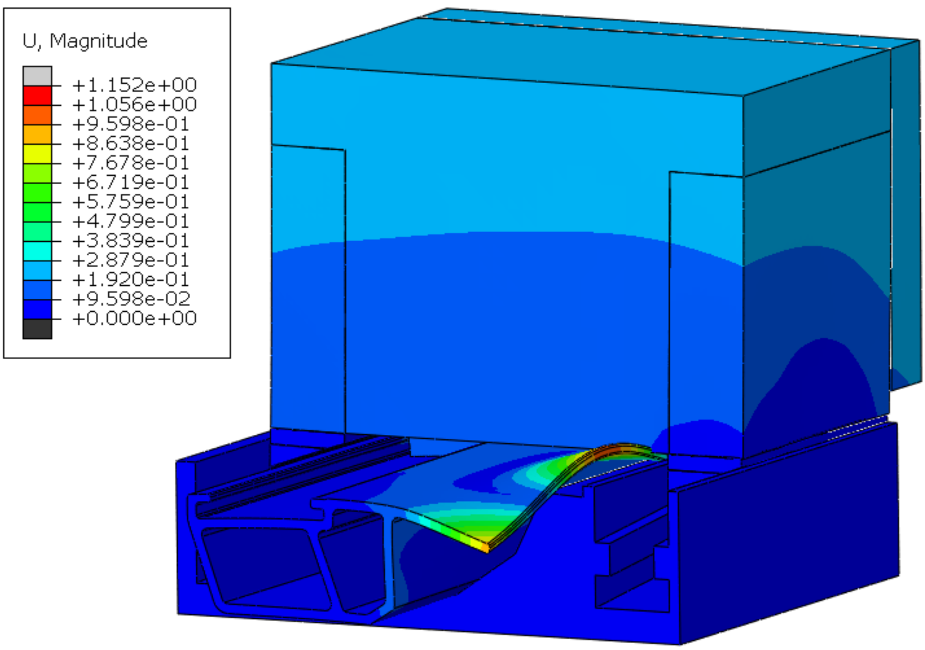


Figure G.1: The frequency mode of 2901.3 Hz

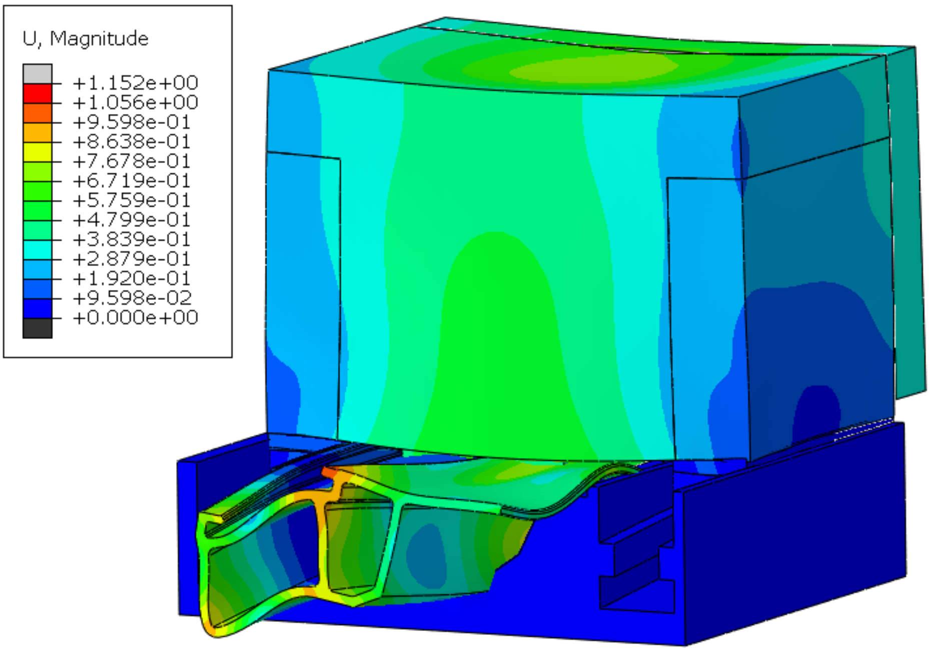


Figure G.2: The frequency mode of 5834.1 Hz

G.2 Contact analysis results

G.2.1 Deformation of the gripping mechanism

The deformation of the gripping mechanism is presented in Fig. G.3. Presented with deformation scale 20.

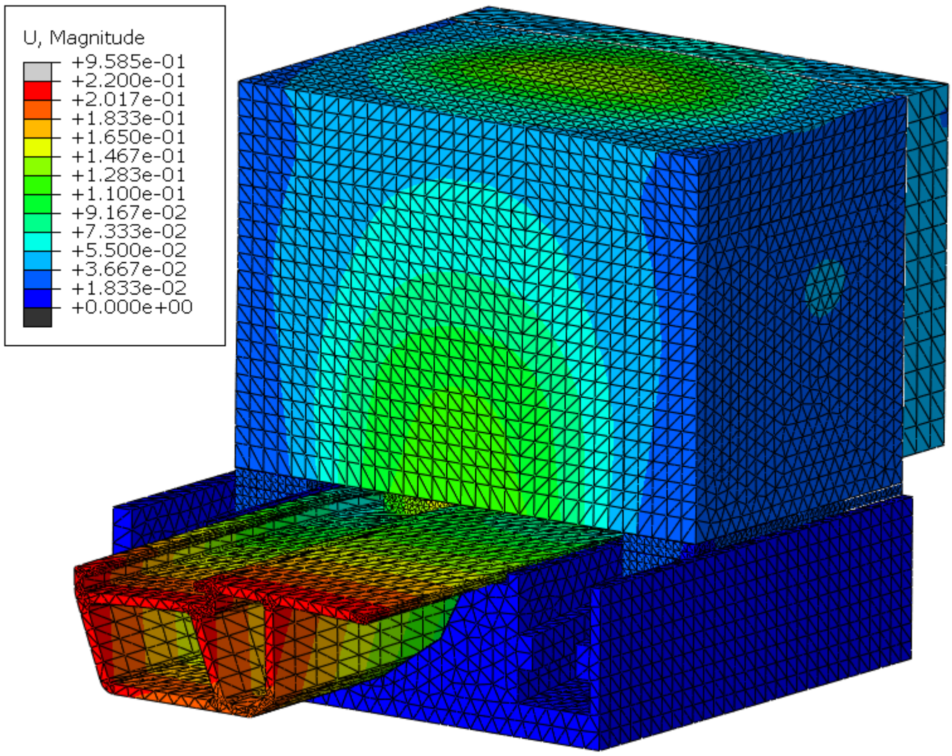


Figure G.3: The deformation of the system

G.2.2 Stress distribution in test product and clamps

The stress distribution in the clamps without and with the clamp inserts is presented in Fig. G.4 and G.5, respectively. The stress distribution in the test product is presented in Fig. G.6. Presented with deformation scale 20.

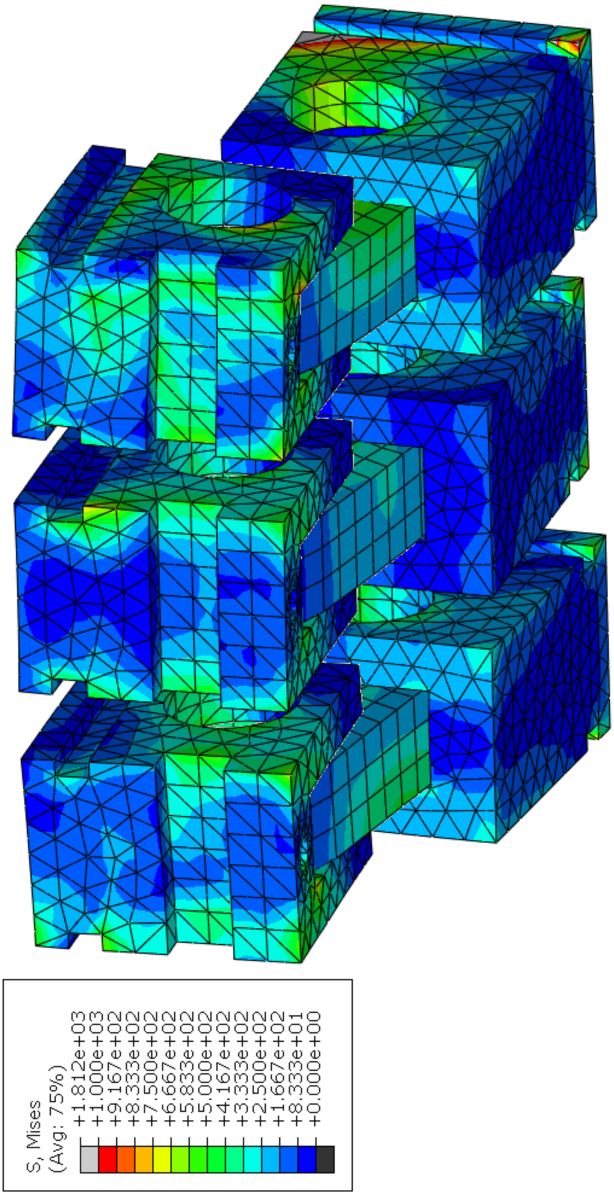


Figure G.4: The stress distribution of the clamps without the clamp inserts viewed from below

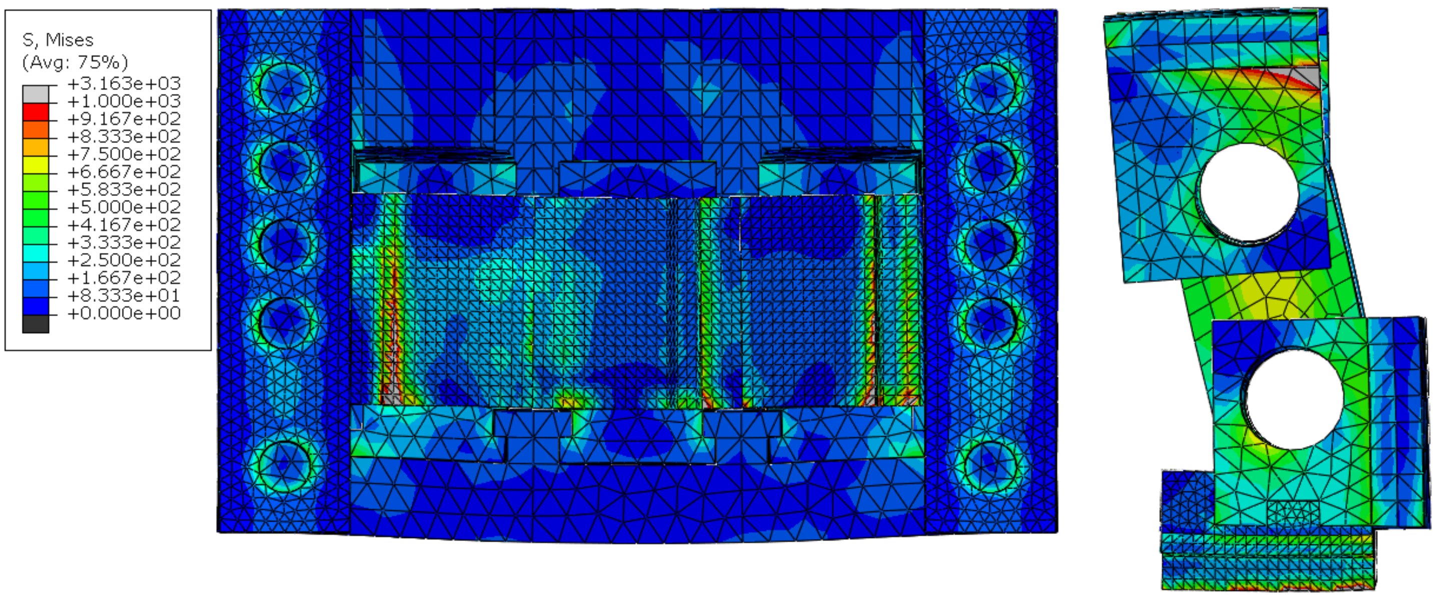


Figure G.5: The stress distribution of the clamps viewed from below (left) and from the side separated from the system (right)

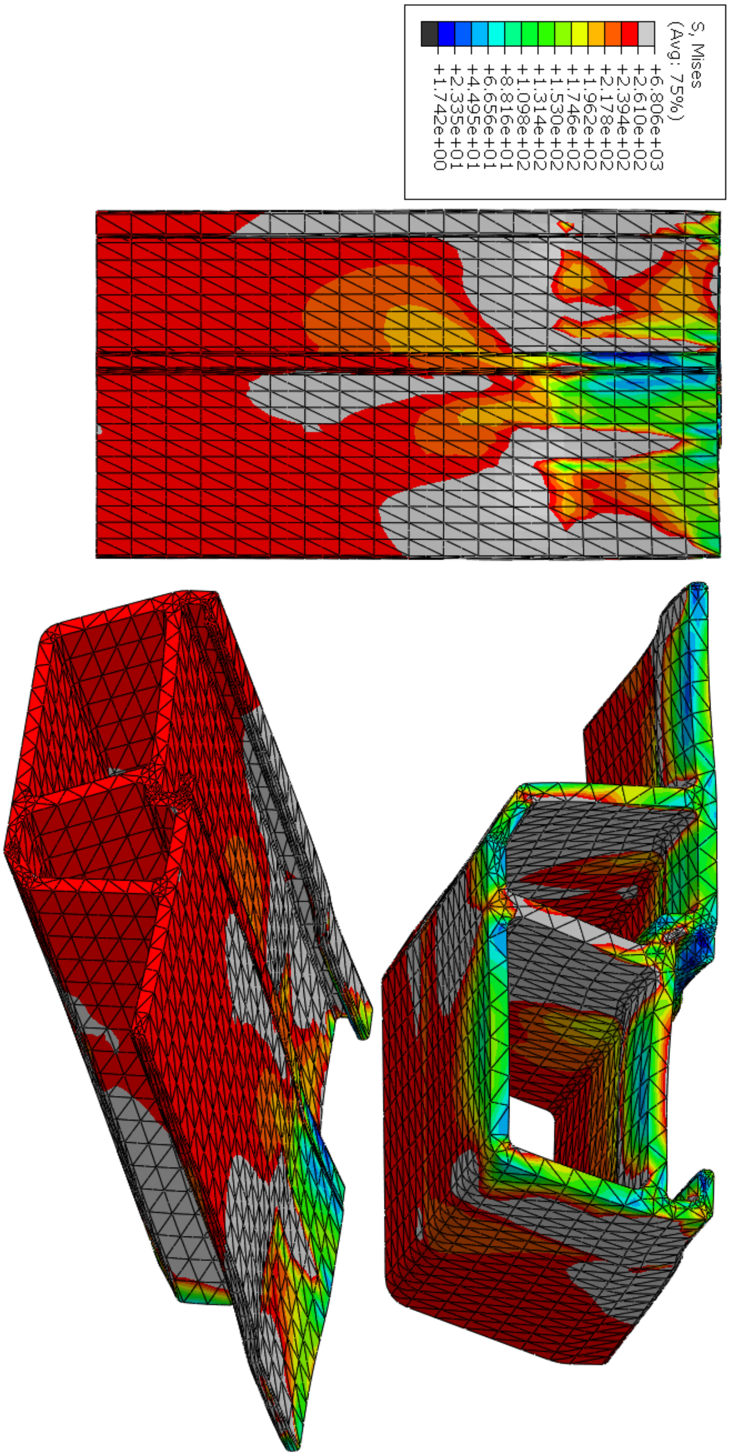


Figure G.6: The stress distribution of the test product viewed from various angles