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Using Prototypes to Leverage Tacit Knowledge

Experimenting with Tacit Knowledge in Product Development

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Submission date: June 2016
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OF SCIENCE AND TECHNOLOGY
DEPARTMENT OF ENGINEERING DESIGN
AND MATERIALS

MASTER'S THESIS SPRING 2016
FOR
STUD.TECHN. JØRGEN ANDREAS BOGEN ERICHSEN AND STUD.TECHN. ANDREAS LYDER PEDERSEN

Using Prototypes to Leverage Tacit Knowledge – Experimenting with Tacit Knowledge in Product Development

We continue exploring the impact of leveraging tacit knowledge in product development – both how it is accumulated, transferred and captured – through prototyping and other value-adding early-stage development activities. Through connections in relevant industries, these topics will be tested in select companies, with possible applicability in their ongoing projects.

The work is a combination of literature, experimental and free early stage conceptual prototyping activities. The indented outcome level should provide a sufficient experimental setup to commence in mid-spring, and work as repository for two possible academic publications later in 2016.

Formal requirements:

Three weeks after start of the thesis work, an A3 sheet illustrating the work is to be handed in. A template for this presentation is available on the IPM's web site under the menu "Masteroppgave" (https://www.ntnu.edu/web/ipm/master-thesis). This sheet should be updated one week before the master's thesis is submitted.

Risk assessment of experimental activities shall always be performed. Experimental work defined in the problem description shall be planed and risk assessed up-front and within 3 weeks after receiving the problem text. Any specific experimental activities which are not properly covered by the general risk assessment shall be particularly assessed before performing the experimental work. Risk assessments should be signed by the supervisor and copies shall be included in the appendix of the thesis.
The thesis should include the signed problem text, and be written as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents, etc. During preparation of the text, the candidate should make efforts to create a well arranged and well written report. To ease the evaluation of the thesis, it is important to cross-reference text, tables and figures. For evaluation of the work, a thorough discussion of results is appreciated.
The thesis shall be submitted electronically via DAIM, NTNU's system for Digital Archiving and Submission of Master's theses.
The contact persons are Sven Bjørkård in Kongsberg Automotive and Prof. Martin Steinert and Achim Gerstenberg at NTNU.

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Abstract

With increasing pressure on knowledge creating companies to innovate faster and better, there is an apparent need for leveraging knowledge transfer – both within the organization and within groups of individuals. While the transfer of explicit information, facts, drawings and data are widely covered by current engineering design research, few efforts highlight the importance of leveraging the tacit knowledge within product development.

This thesis aims at enabling this tacit knowledge transfer; the learnings, insights and experiences, through the use of prototypes in the early stages of development. Aimed at both practitioners and academics, this thesis presents three academic papers, containing a theoretical framework for exploring said knowledge transfer. Additionally, a thorough elaboration of select theoretical topics is presented, meant to supplement the content of academic papers.

To further explore the use of prototypes for knowledge transfer in product development, a two-part controlled research experiment has been designed and run using 33 participants being either professional practitioners or mechanical engineering graduate students. Here, we test the impact of (both high and low) prototype affordance on three hypotheses; the ‘Problem and Concept Understanding Hypothesis’, the ‘Design Fixation Hypothesis’ and the ‘Learning Activity Hypothesis’. In our results, we find some statistical support for stating that prototype affordance has a significant impact on concept evaluation (and therefore understanding). However, we also find that there is not enough evidence to state that prototype affordance has a significant impact on either problem understanding, design fixation or quality of design. Lastly, insights containing interpretations, limitations and implications are presented, stating that there is a need for further exploration of knowledge transfer through prototypes.

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Sammendrag

Med økende behov for å innovere fortere og bedre, må kunnskapssentrerte selskaper og organisasjoner stadig øke fokuset på å overføre kunnskap – både innad i organisasjonen og mellom organisasjonens individer. Selv om overføring av eksplisitt informasjon, fakta, tegninger og kunnskap er godt ivaretatt innenfor ingeniørvitenskapen, er det få som poengterer viktigheten av å vektlegge den såkalte tause kunnskapen.

Denne masteroppgaven sikter på å øke kompetansen rundt overføring av taus kunnskap; læring, erfaring, innsikt og forståelse, gjennom bruken av prototyper i tidligfase produktutvikling. Med utgangspunkt i å skulle favne et bredt publikum – fra både akademia og industrien – presenteres tre publiserte forskningsartikler. Disse inneholder et teoretisk rammeverk for utforskning av taus kunnskap i produktutvikling. Videre er det også vedlagt en større utdypning av noen teoretiske emner, tiltenkt å skulle supplere innholdet i de akademiske tekstene.

For å kunne videre utforske bruken av prototyper til bruk i kunnskapsoverføring innen produktutvikling har et todelt forskningseksperiment blitt satt opp og gjennomført. Dette eksperimentet er gjennomført med 33 deltakere fra både næringsliv og studentmasse, og tar sikte på å utforske effekten av å variere en prototype sin 'affordance' (Norsk. 'båndbredde' eller 'tilbydelighet') i tidligfase prototypeaktiviteter. I eksperimentet testes hypotesene; 'Problem and Concept Understanding Hypothesis' (Norsk. 'Problem og Konseptforståelseshypotesen'), 'Design Fixation Hypothesis' (Norsk. 'Fikseringshypotesen') og 'Learning Activity Hypothesis' (Norsk. 'Læringshypotesen').

Våre resultater peker i retning av at det finnes statistisk belegg for å si at en prototype sin 'affordance' har en signifikant betydning for konseptevaluering (og derfor konseptforståelse) i tidligfase produktutvikling. Videre ser vi manglende statistisk grunnlag for å kunne fastslå en definitiv forskjell mellom gruppene hva gjelder problemforståelse, fiksering og kvalitet. Avslutningsvis gjøres det bemerkninger rundt tolkning av resultater, begrensninger og betydninger av forskningen, og et økende behov for forskning på overføring av taus kunnskap gjennom prototyper poengteres.

To copious amounts of coffee, ambiguity,

and the need to prove a point.

Acknowledgments

This research is supported by the Research Council of Norway through its user-driven research (BIA) funding scheme, project number 236739/O30. In addition, we would like to express special gratitude towards Kongsberg Automotive, who have shown collaborative spirit and goodwill.

Lastly, this thesis would not have been complete without the support from close friends, girlfriends and family. We sincerely thank you all.

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Reader's Guide

This thesis is written with both academics and industry experts of early phase research and development activity in mind. The theoretical basis and the performed study is aimed at providing insights into the real-world problems of everyday practitioners, while the related articles are aimed at fusing these insights to make an academic contribution.

The thesis consists of two main parts: Part I: A general introduction and overview, and Part II: The Published articles, written with regards to the contents of Part I.

Part I:

A general overview of the literature review, theory, method and results of the study performed for this thesis. The theoretical background of Part I is aimed at being complimentary to the appended articles, in an attempt to not repeat information, but rather to add to the existing framework of the appended articles.

Part II:

The articles published by the authors, supplementing the thesis. Altogether, three articles have been submitted and accepted to peer reviewed conferences, and will be published in the respective conference proceedings. Moreover, the proceedings containing both Research Papers II and III are scheduled for being published as journals publications.

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List of Research Papers

Research paper I

Using Prototypes to Leverage Knowledge in Product Development: Examples from the Automotive Industry

Erichsen, Jorgen A. B., Andreas Lyder Pedersen, Martin Steinert, and Torgeir Welo. "Using Prototypes to Leverage Knowledge in Product Development: Examples from the Automotive Industry". I: 2016 IEEE International Systems Conference (SysCon 2016) Proceedings. Orlando, Florida: IEEE 2016 ISBN 978-1-4673-9518-2. s. 491-496

Research paper II

Learning in Product Development: Proposed Industry Experiment Using Reflective Prototyping

Erichsen, Jorgen A. B., Andreas Lyder Pedersen, Martin Steinert, and Torgeir Welo. "Learning in Product Development: Proposed Industry Experiment Using Reflective Prototyping". Procedia CIRP. http://doi.org/10.1016/j.procir.2016.04.142

Research paper III

Prototyping to Leverage Learning in Product Manufacturing Environments

Erichsen, Jorgen A. B., Andreas Lyder Pedersen, Martin Steinert, and Torgeir Welo. "Prototyping to Leverage Learning in Product Manufacturing Environments". Procedia CIRP, June 2016. doi:10.1016/j.procir.2016.04.099.

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Part I: Introductory Overview

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1 Introduction and Background

This thesis aims at exploring how to leverage tacit knowledge in product development through the use of prototypes. Parts of the work portrayed in this thesis is done in collaboration with Kongsberg Automotive, a multinational Tier 1/2 automotive supplier based in Kongsberg, Norway. This collaboration started in the fall of 2015, when we (the authors) wrote our project thesis – exploring the theoretical foundation of tacit knowledge transfer in product development. During this period, we have had several visits at Kongsberg, including a full week of running experiments with Kongsberg employees.

Through our review of the current practices in a real world setting, we gained insight into challenges that may arise during early phase product. Kongsberg Automotive is among the world leading in their core markets. The information they shared with us has been extensive, and showed a company with skilled engineers and good project structure. However, there is a fear of not being able to stay ahead of the curve, as the globalized markets evolve rapidly. In such an environment, where the company is dependent on bringing new and innovative solutions to market in order to satisfy emerging customer needs, a good structure for efficient early phase exploration and pre-stage-gate development is necessary.

The intrinsic study of the product development practices at Toyota, done by Ward, Liker, Cristiano & Sobek II (2012), cultivated a new trend within the engineering design community. The Toyota practice is summarized well by Morgan & Liker (2006) in their 13 principles of Lean product development, identifying Toyota's treatment of process, people and technology. Similarly, the work at IDEO (Kelley & Kelley, 2013) has spiked an awareness of the potential of prototyping in the early phase of product development, through their extensive use of quick ideation and rapid prototyping cycles, extracting models from their own favorable work and applying it with great success. The theoretical groundwork by Polanyi (1966) on tacit knowledge elaborates on the dimension of knowledge which is not explicit, yet applied and necessary. The tacit knowledge framework can explain how learning takes place from the perspective of knowledge management. Specifically, the work by Nonaka (1994) presents how knowledge is acquired and accumulated at an individual and organizational level, through his model of dynamic knowledge creation.

The theoretical basis of this thesis is grounded in product development, and the exciting role that prototyping can play. As the project thesis leading to this Master's thesis was deemed classified because of the containing details of Kongsberg Automotive's practices, it is not appended. However, the appended Research Papers contain the essentials.

The issue of early phase product development is a challenge in many settings. In Research Paper I, we take the scope of the automotive industry. As the organizational knowledge and prototyping literature is combined, we present the Audience-Intent Model for prototyping, and present two case examples of knowledge being transferred from prototypes. Expressing the need for knowledge transfer and learning in product development, giving emphasis to the potential of internal, reflective prototyping.

In Research Paper II, the importance of affordance in prototyping and the role of design fixation in ideation is added to the existing literature basis of prototyping and knowledge transfer. As our research culminated into an experiment using internal, reflective prototyping, we wrote a paper on the proposed experiment. At this point we had all the theory in place, but had not run experiment pilots yet. Thus, the final experiment described in Chapter 3, is not completely similar to the one described in the paper.

As efficient knowledge acquisition, or learning, is key to yield research and development results at a cost, we explore the learning potential by applying reflective prototyping. Two examples from industry settings are presented in Research Paper III. Firstly, a case where the use of internal reflective prototyping saved time and labor. Secondly, a case where the lack of an undiscovered, unknown problem caused the system to occasionally fail. Thus, we discuss how reflective prototyping could have avoided the problem.

In Chapter 2, we explore theory regarding knowledge transfer in product development, its relation to prototyping, and present the basis for the practices tested in said research experiment. Chapter 3 attempts to give a thorough description of the experiment setup, including variables, equipment and procedure. Results are presented in Chapter 3.6.3, and include descriptive statistics, statistical analyses, evaluation of hypotheses, and interpretation of data. Lastly, select limitations (Chapter 5), implications (Chapter 6) and conclusions (Chapter 7) are presented, presenting our reflections and insights gathered throughout working with this thesis.

2 Theory: Knowledge Transfer and Prototyping

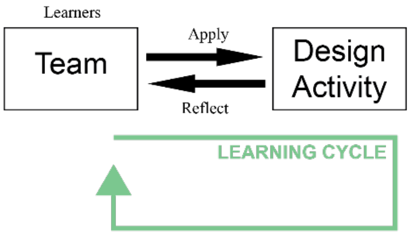

Figure 1 - The learning cycle that occurs in a team during a design activity.

In product development, the design team aims to create deliverable output as part of the product development process. The work can be modelled as seen in Figure 1, representing the learning cycle that occurs when a team applies existing knowledge, and subsequently reflects upon this application. This learning cycle is applicable to each individual, affecting individual knowledge, but also the group's combined knowledge.

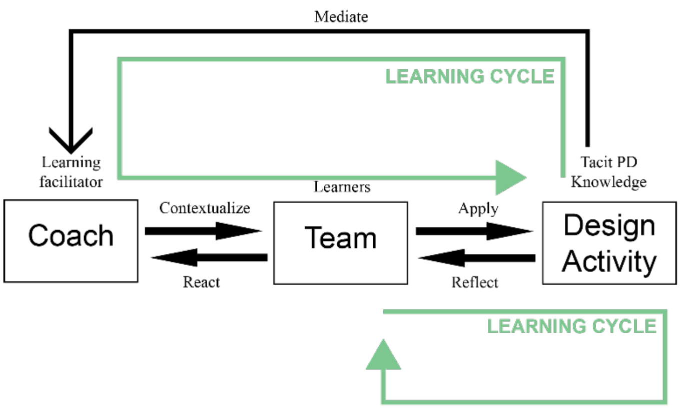

Figure 2 - The learning cycles that occur when including learning facilitators in a team (during design activities), as formulated by Leifer & Steinert (2011).

Similarly, knowledge application and reflection applies when including coaches, meant to provide feedback and facilitate the design activity. Through this facilitation, the team and coach create another learning cycle, as modelled in Figure 2. Both of these two learning cycles are relatively informal processes, and the formal outputs are project deliverables. Additionally, these learning cycles provide experience for the design team members and facilitators.

The formal output (i.e. explicit knowledge) is generally captured as part of organization PLM or project management systems. However, the informal output, consisting of insights, experiences and learning which enable the members of the design team in the product development process, is what we refer to as tacit knowledge, and is harder to capture and store.

Expanding the view to the product development organization induces an additional learning cycle, and the model in Figure 3 in its entirety, as prompted by Eris & Leifer (2003) and built upon by Leifer & Steinert (2011). The formal component aims to capture learning from the design activity to use in later projects, requiring formalization of the project output. As the explicit knowledge is already formalized it can be stored easily, while the tacit knowledge is not stored in a formal manner.

The tacit knowledge theory was induced by Polanyi's (1966), and is applied to explain the complicated nature of knowledge (Holsapple & Joshi, 2001), the creation of knowledge within knowledge management (Nonaka, 1994), and within the requirements engineering branch of software engineering the tacit knowledge framework has been embraced in the search for new, innovative products (Gervasi et al., 2013).

Corresponding to the learning cycle model by Leifer & Steinert (2011), which depicts the difference between the formal and informal knowledge exchange, we can also differentiate between explicit and tacit knowledge. The challenge in knowledge creation and accumulation in organizations is formalizing the knowledge created in the learning loops of the design team, and to make this output explicit, as to preserve knowledge and benefit from former efforts.

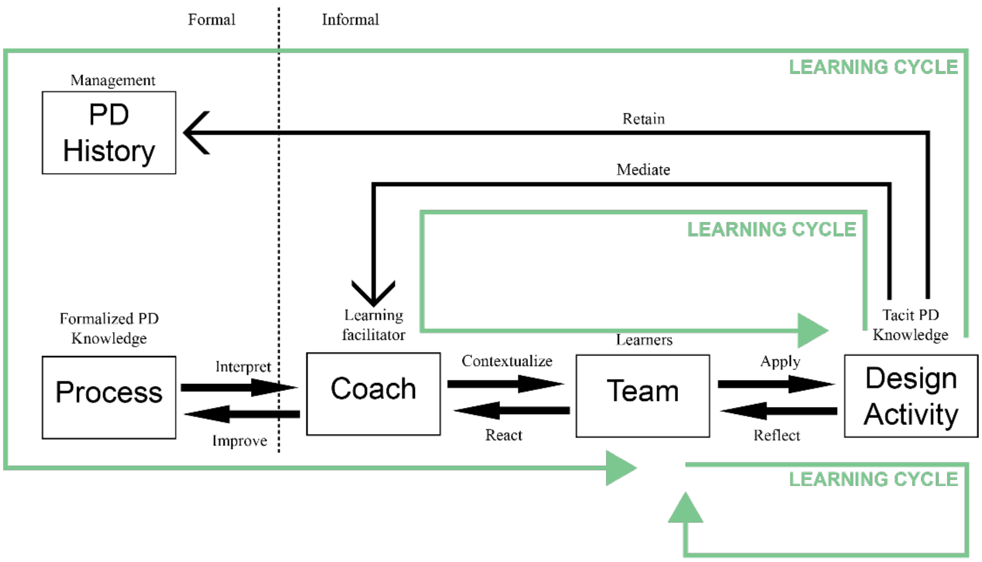

Figure 3 - The three learning cycles of the product development organization, as formulated by Leifer & Steinert (2011). Figure adopted from Research Paper I.

2.1 The Dynamic Knowledge Creation Model

The dynamic theory of organizational knowledge creation was introduced by Nonaka (1994), and has since been widely recognized. The model attempts a paradigm shift by viewing knowledge in organizations as created and existing between individuals, rather than in the within processes of an organizational structure. Thus, regarding the tacit knowledge of individuals in the organization as part of the organizational knowledge. This section will cover the SECI knowledge spiral (Figure 4), organizational knowledge assets, and the enabling conditions for knowledge creation.

2.1.1 The SECI Knowledge Creation Spiral

The knowledge spiral represents the conversion of tacit and explicit knowledge in an organization, and the creation of knowledge occurring when spiraling through the stages. The stages of the SECI process is described in detail in the appended Research Papers I, II and III (Erichsen, Pedersen, Steinert & Welo, 2016a, 2016b, 2016c). Primarily, the stages

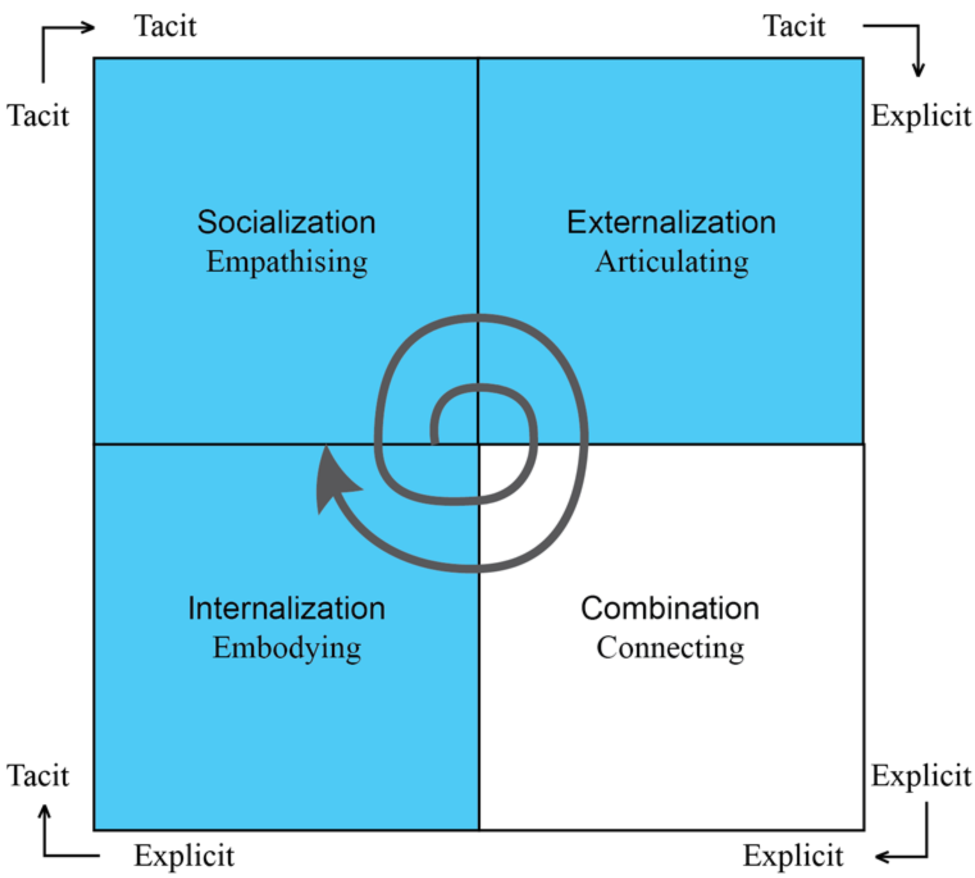

Figure 4 - The SECI knowledge creation spiral, as articulated by Nonaka (1994). Figure taken from Research Paper III.

of Socialization (tacit-to-tacit), Externalization (tacit-to-explicit) and Internalization (explicit-to-tacit) are discussed with regards to learning activities in product development. The forth step of the SECI process, Combination (explicit-to-explicit), can be described as a repository for implemented knowledge where the formalized knowledge can be distributed within the organization.

2.1.2 Knowledge Assets

Concerning the knowledge spiral, Nonaka, Toyama & Konno (2000) introduces accompanying knowledge assets to work as knowledge carriers between the stages of knowledge conversion. With the SECI spiral, the knowledge assets form the basis of the knowledge creation process. A company's ability to exploit existing knowledge and create new knowledge depends on the understanding of its knowledge assets.

2.1.2.1 Experiential Knowledge Assets

Experiential knowledge assets consist of the tacit knowledge shared between the members of the organization through shared individual skills and hands-on experience. Other examples are interpersonal emotional assets such as care, love and security between members, and physical expressions such as gestures and passion. In its essence the experiential knowledge assets are the ability of the members of the organization to function together on a personal level, thus enabling cooperation. By nature, they are hard to grasp or evaluate, but of vital importance to an organization.

2.1.2.2 Conceptual Knowledge Assets

Conceptual knowledge assets consist of explicit knowledge represented by images, symbols and language. These might be product concepts, brands or designs. Tangible by nature, they are easier to grasp than experiential knowledge assets, although it is difficult to extract what customers or other organization members perceive.

2.1.2.3 Systemized Knowledge Assets

Systemized knowledge assets consist of systemized, explicit knowledge, such as databases, documents, manuals, patents or licenses. These are easily transferable, visible assets.

2.1.2.4 Routine Knowledge Assets

Routine knowledge assets consist of tacit knowledge embedded in the practices of the organization. Examples are know-how in the daily activities, organizational routines and culture. These patterns of thinking and action are structures for imposing current practices onto members of the organization. Thus, a course of actions intentionally set for implementing practices can bring explicit knowledge into the organization as tacit knowledge.

The logical argumentation of this thesis assumes and argues for considering prototypes as conceptual knowledge assets, and the prototyping activity to be essential for the knowledge creating process related to conceptual knowledge assets. As described by Nonaka et al. (2000), conceptual knowledge assets have tangible forms. Although easier to perceive than the intangible experiential knowledge assets, the perceivable information provided by the object and the individual interpretation of the object meaning (i.e. affordance and semantics (You & Chen, 2007)), respectively) of the articulated image, description or model can be hard to anticipate or control. Thus, the experience of creating the object, either conveyed or experienced personally, can be the necessary factor for all members to interpret a concept similarly.

The study by Chou & He (2004) concludes conceptual knowledge assets to have the most significant effect on knowledge creation processes, while systemic knowledge assets have the least significant effect. Both internalization (explicit-to-tacit) and externalization (tacit-to-explicit) are significantly influenced by conceptual knowledge assets, whereas socialization is most influenced by routine knowledge assets. Thus, indicating the transfer between tacit and explicit knowledge to be most influenced by conceptual knowledge asset. Similarly, the systemic knowledge assets' low effect in knowledge creation can be explained by its exploitative nature, opposed to the explorative nature of knowledge creation, as is described by Martin (2009).

2.1.3 Enabling Conditions

The enabling conditions of the dynamic knowledge creation model are 'intention', 'autonomy', 'fluctuation' and 'creative chaos', 'redundancy' and 'requisite variety', as introduced by Nonaka & Takeuchi (1995). These are necessary to facilitate the knowledge creation accumulated through the knowledge spiral and the administration of knowledge assets. Besides 'Ba', the shared context of dynamic knowledge creation emphasized by Nonaka et al. (2000), the enabling conditions are essential at organizational level to promote the knowledge spiral.

2.1.3.1 Intention

Intention is a term used to describe the need for a set goal of operations. Including strategic intention, objective, or simply a vision of the knowledge the organization should aim to create. The intention of the organization provides a frame of judgement for the members to value the information in their environment, and provides an arrangement of fundamental values.

2.1.3.2 Autonomy

Autonomy as an enabling condition emphasizes the importance of allowing all members of an organization to act as autonomously in their operations as the conditions allows, to increase the possibility of introducing unexpected opportunities. Coupled with transparent intentions, permitting autonomy increases the commitment of the individual. Hence, by facilitating autonomous work, an organization authorizes members to remain flexible and committed.

2.1.3.3 Fluctuation and Creative Chaos

Fluctuation and creative chaos is valued in the context of knowledge creation, as it allows renewal of the organization and reconsidering old habits and attitudes. When breakdowns occur, individuals reconsider the fundamental thinking and their perspective, which might lead to questioning of basic attitudes and realignment of commitment. However, in order to create “order out of chaos” reflection is essential. Without the influence of reflection, fluctuation have an inclination to lead to “destructive chaos”.

2.1.3.4 Redundancy

Redundancy is intentional overlapping of information. The use of redundancy as a positive factor is counterintuitive to western management culture, as the heed for efficiency focuses strongly on the depletion of redundancy, since the term is associated with unnecessary duplication, waste and information overload. Although the abundance of information tends to lead to spreading of tacit knowledge, the fear of information overload is not ungrounded, and abundance of information will cause an increased cost of knowledge creation in the short term.

2.1.3.5 Requisite Variety

Requisite variety assures members of the organization a variety in tasks, allowing an assortment of hands on experience. The tacit knowledge obtained from monotonous tasks will decrease if extended over a long period. Doing occasional organizational restructuring, moving members around, and developing a flat and flexible organizational structure to ease such restructuring will make sure the members' tasks are not routine, and facilitate the creation of tacit knowledge.

In addition to the enabling conditions, 'Ba' is essential to aid the knowledge spiral. It is described by Nonaka et al. (2000) as "shared context in motion for knowledge creation". Ba provides energy and quality to perform the individual conversions between tacit and explicit knowledge and move along the knowledge spiral.

According to Nonaka et al. (2000), unifying the elements of the model of dynamic knowledge creation will enable organizations to manage the knowledge creating process effectively, by recognizing its dynamic nature. Of these topics, we identify the SECI knowledge creation spiral and the role of the conceptual knowledge assets as being the most important factors for knowledge creation, and will consequently focus on these throughout the thesis. Additionally, conceptual knowledge assets are also identified by Chou & He (2004) as the most influential in knowledge creation. Nonaka & von Krogh (2009) calls attention to further research opportunities and the critique made regarding the model of dynamic knowledge creation. These predominantly attend to the relationship between organizational knowledge creation and social practices in organizations. That is, the implementation of 'Ba' as the social context where knowledge is created, or establishing of an organizational culture. This is closely related to the recognition and use of the knowledge assets in the organization.

2.2 Tacit Knowledge in Requirements Elicitation

Requirements engineering has sprung out of software engineering, and although somewhat outside the scope of the experiment performed in this thesis, we suspect great potential in the application of this theoretical groundwork in requirements elicitation. Consequently, this section will serve as a comment to the role of prototypes and learning in requirements elicitation and the search for the unknown problems.

In the requirements elicitation phase of requirements engineering, tacit knowledge poses a great challenge. Missing or mistaken requirements will cause exceeding costs and project delays. The current practice is largely based on stakeholder interviews (e.g. Sutcliffe & Sawyer (2013) and Zappavigna & Patrick (2010)). A review made by Davis, Dieste, Hickey, Juristo & Moreno (2006) on the available empirical evidence, notably studies done by Goodrich & Olfman (1990), Moore & Shipman (2000) and Engelbrektsson (2002), show that the use of prototypes during the elicitation interviews tend to result in fixation on the artefact, and that crucial information not encompassed by the artefact will not be exposed. The role of design fixation in prototyping is discussed in section 2.4. This section will make a brief review of the current practices, and present a framework for the potential of learning by applying the reflective prototyping approaches presented in section 2.3.2.

2.2.1 Requirements Elicitation Terminology

The issue of the relative knownness of knowledge, and who possesses it, was made famous by Donald Rumsfeld’s press briefing at the US department of defense, stressing the difficulties of the “known knowns, the known unknowns, and unknown unknowns” when treating security intelligence. Gervasi et al. (2013) propose a Tacit Knowledge Framework, and properties are defined for the known and unknown knowns and unknowns. ‘Expressible’ describes known knowledge; ‘articulated’ describes the documented known knowledge; ‘accessible’ describes the knowledge which is in not the foreground of the mind; ‘relevant’ describes the relevancy to the project.

By origin, this set of terms are compiled to describe requirements elicitation by stakeholder interview, from the interviewer’s point of view. The most favored practice in requirements elicitation is interviews, be it structured or unstructured (Davis et al., 2006) (i.e. the socialization stage of the SECI knowledge creation model by Nonaka (1994)). Gervasi et al. (2013) focus on the unknown knowns, i.e. knowledge the interviewer is not aware of, but the interview subject possesses and does not share. There could be a variety of reasons for not sharing, such as a perceived personal interest in not exposing the knowledge, the knowledge not being in the front of the subject’s mind (i.e. tacit knowledge), or problems with articulating the information causing the subject to avoid the topic.

2.2.2 Categorization by Expressibility and Exposure

This section does not focus on the interview process, but rather on 1) the work done by a team or an organization in attempting to elicit requirements they are not able to get from stakeholders, and 2) on the same team or organization’s exploration for new questions to propose, internally and externally.

To quote Gervasi et al. (2013); “An unknown unknown is an item of knowledge that the analyst has not successfully elicited from the customer, but in this case, the analyst is unaware that it exists. Thus, the analyst will never elicit the knowledge unless something happens to make them aware that it exists.” Thus, acknowledging the limited capability of interviews in exposing the unknown unknowns.

We expand the tacit knowledge framework by Gervasi et al. (2013) by adding another term, ‘exposure’, describing whether the need for the knowledge is exposed (i.e. have someone identified the specific missing knowledge in the domain). This brings us to setting the metric shown in Figure 5.

		Exposure of the need for knowledge	
		Not exposed	Exposed
Expressibility of knowledge	Expressible	Unknown knowns • Possessed as tacit knowledge • Good enough – for now *Not articulated, potentially accessible*	Known knowns • Possessed as explicit knowledge *Articulated and accessible*
	Not expressible	Unknown unknowns • Present or future problem, yet to be discovered *Not articulated, not accessible*	Known unknowns • A good start • A chance to avoid the issue *Not articulated, but accessible*

Figure 5 - The known (i.e. the knowledge exposed by the organization, and identified to be relevant), the unknown (i.e. the knowledge not exposed by the organization, though possibly relevant), the knowns (i.e. knowledge possessed by the organization) and the unknowns (i.e. knowledge not possessed by the organization).

2.2.3 Establishing Knowledge Alteration Processes

Once the categorization metric is established, we can formalize the processes of moving between the categories, either altering the unknown into known, or the unknowns into knowns. Hence, recognizing the association to current product development practice and theory. The processes are as follows:

Process 1 (Unknown unknowns to unknown knowns) is knowledge made expressible without exposing the lack of said knowledge (i.e. creating tacit knowledge). By making the knowledge expressible it is accessible to the organization, but not yet accessed.

Process 2 (unknown knowns to known knowns) is exposing tacit knowledge by explicitly expressing it, converting tacit knowledge into explicit knowledge. Hence, this process resembles the externalization stage of the SECI model of Nonaka (1994).

Process 3 (unknown unknowns into known unknowns) is exposing missing knowledge, but not being able to express it (i.e. exposing a lack of certain knowledge regarding a product requirement, or a lack of competence within an organization). Trying to articulate problems requires exploration of unknown areas.

Process 4 (known unknowns to known knowns) is expressing knowledge already identified as missing in the organization. E.g. typical engineering tasks, such as well-specified technical problems, resulting in explicit knowledge.

The processes 1-3 bear similarities to the wayfaring approach to needfinding, described by Gerstenberg, Sjöman, Reime, Abrahamsson & Steinert (2015) and Steinert & Leifer (2012). They present the Hunter-Gatherer model for exploring the concept discovery space by way of wayfaring, doing numerous iterations of building prototypes, testing, learning and reevaluating the further course of development. Hence, involving explorative activity to enable the discovery of unknown problems and solutions.

2.3 Types of Prototyping

In the appended Research Papers I, II and III, a short definition of prototypes and prototyping is made, mainly based on the work by Eppinger & Ulrich (1995). Their work regards prototypes for early phase product development as brief representations of what the concept idea is. Further, prototypes are regarded as concept milestone representations in the late phase, as part of a rough stage gate model, securing the project progress (i.e. alpha prototypes, beta prototypes, pre-production prototypes). Ullman (2009) considers four categories of prototypes: proof-of-concept, proof-of-product, proof-of-process and proof-of-production. In the case of the model by Ullman (2009) prototyping is used for the purpose of verification and validation, and prototypes are merely a tool. As expressed by Elverum & Welo (2015), beyond the verification and validation purpose, prototypes aid learning in “Framing of design problems and exploration of various possibilities related to the design”. The study by Bacon, Beckman, Mowery & Wilson (1994) found that prototyping lead employees to discover flaws and uncover surprises that would not have been uncovered in other ways. Thus, assisting in solving unknown problems.

A wider use of the term prototyping is applied by Buchenau & Suri (2000), by describing the activity in IDEO as experience prototyping. More recently the term physical computation was coined by Foehr, Stuecheli & Meboldt (2015), describing work with low fidelity prototypes to do coarse measurements for comparing data with a numerical analysis. This method can discover unarticulated problems with a concept design before more expensive and time consuming methods are applied. This greatly affected the necessary time for validating the design and the confidence in the design before ordering a prototype with high lead time.

2.3.1 Select Prototyping Models

Beyond the aforementioned models, several extensive models on prototypes and how to apply them as a part of the product development process have been developed, and we have chosen to take a closer look at three of them.

2.3.1.1 Houde and Hill's Prototyping Model

Firstly, Houde & Hill (1997) focus on the purpose of the prototype by classifying the questions which are important to a design. ‘Role’ refers to questions regarding the useful functions an artifact serves to a user. ‘Implementation’ refers to questions regarding the techniques and components through which the artifact performs its function. Further, ‘Look and feel’ refers to the questions regarding the sensory experience of using the artifact, i.e. what the user sees, feels and hears while using it. Houde & Hill's (1997) model give developers the ability to explicitly separate the design issues into three classes, make the purpose clear, and visualize the focus of exploration.

2.3.1.2 Bryan-Kinns and Hamilton's Prototyping Model

Secondly, Bryan-Kinns & Hamilton (2002) provides a framework to explore the use of prototypes by three dimensions of representation. ‘Fidelity’ is the concept representations accuracy as to the actual imagined concept (e.g. hand drawn sketches are low in fidelity, while a fully interactive computer based representation including graphical layout is high in fidelity). ‘Target audience’ range from the internal audience (i.e. the organizations own engineers) to external audience such as clients. ‘Stage of development’ denotes the differentiation between using prototypes for requirements analysis and using them for testing. This model attempts to divide prototyping into categories based on the purpose (i.e. audience and development stage) against the time and resources put into the building of the prototype (i.e. fidelity). Other dimensions, mentioned but not taken into regard by the model, are the tools, the ability of the designers, accessibility of the stakeholders and integration with other tools.

2.3.1.3 Elverum and Welo's Prototyping Model

Thirdly, the prototype value model presented by Elverum & Welo (2016) partitions prototypes into three categories and three levels. The three levels represent the value contribution's dependency on the level the prototype is considered from. That is, organization, system, or component level. Further, the process category is comprised of the process applied in building the prototype, ranging from cobbled up (e.g. rough, early stage functional prototypes) to actual production processes as used in the final product (e.g. production-intent prototypes). The artefact category relates to the resemblance to the intended final product, in the same way the fidelity term is used by Bryan-Kinns & Hamilton (2002). The experiment category is what is most highlighted in the product development literature regarding prototyping. The potential of these prototypes is the verification and validation of the design and exploration of unanticipated anomalies, with the executed experimentation ranging from exploratory to confirmatory. This categorization model maps the value created, as is central in the lean product development literature (Welo, 2011). The process category value potential is the learning made in the process of making the prototype, the artefact category value potential is the physical artefact created in the process of prototyping, while in the experiment category the value potential is in the data created from the experimentation.

Elverum & Welo (2016) emphasizes the difference between prototyping done in the automotive industry by European and Japanese automakers. The focus, when prototyping in Japanese companies, is the prototype as a platform of learning – identifying problems with the designs. Hence, learning from the process is a valued aspect of the prototyping. The European counterparts focus on building the best possible prototype as seen from the customers' point of view, entailing a more manual build without much thought offered towards mass production, and the value of the prototype being the artefact. This is not to say one approach is better than the other, but that both approaches have its purpose, and can add value to the product development process.

2.3.2 The Audience-Intent Model

The product development models by Eppinger & Ulrich (1995) and Ullman (2009) does not rely on prototypes during the early phases of development. Meanwhile, the findings by Bacon et al. (1994) and Foehr et al. (2015) identifies the important role of prototypes in learning in product development, especially in the early phase. Doing thorough work before selection and extensive decision making is promoted by the Lean product development and concurrent engineering communities. Efficient knowledge creation in the early phase of product development projects will facilitate exposure of the unknown problems early on. Hence, implementation of the model of dynamic knowledge creation, applying the SECI process and the treatment of knowledge assets to assure conversion and creation of tacit and explicit knowledge in the early phase, will save the organization time, money, and labor.

Applying the explorative use of prototyping contains great potential regarding the importance of learning activities and discovering unknown unknowns in the early phase. The Audience-Intent Model presented in the appended Research Papers I, II and III describe the distinction between external and internal audience, and reflective and affirmative intent when prototyping, in order to further investigate this potential. Additionally, this distinction results in a two-by-two metric (Figure 6), and the four mapped categories are described in detail. In particular, a clear connection is made with the SECI knowledge creation process, the conceptual knowledge assets, and examples from industry are presented.

The audience categorization corresponds to the “target audience” category in the model by Bryan-Kinns & Hamilton (2002), although the term internal is extended to include an individual, a few individuals, or a team, in addition to the company as a whole. The intent categorization takes no regard of what fidelity or in which stage of the product development process the prototype is made. The intent regards the organizations interests from a personal perspective, recognizing the organization’s interest in learning and creating new tacit knowledge among its members.

The scope of this model leaves many dimensions of prototyping unattended to, such as those described by Houde & Hill (1997) and Bryan-Kinns & Hamilton (2002), but it rather illuminates the learning potential. However, the learning perspective is reflected in the formulation by Houde & Hill (1997), as the questions one would ask about the prototype as the basis for categorization, indicating the value of the prototype to be embedded in the creation and interaction with the object, not in the object itself. The framework established by Elverum & Welo (2016) clearly recognizes the value of the process of creating the prototype. They include the cobbled up, rough prototyping process, as a recognition of the prototyping practices of Japanese automakers, using prototyping as a platform for learning.

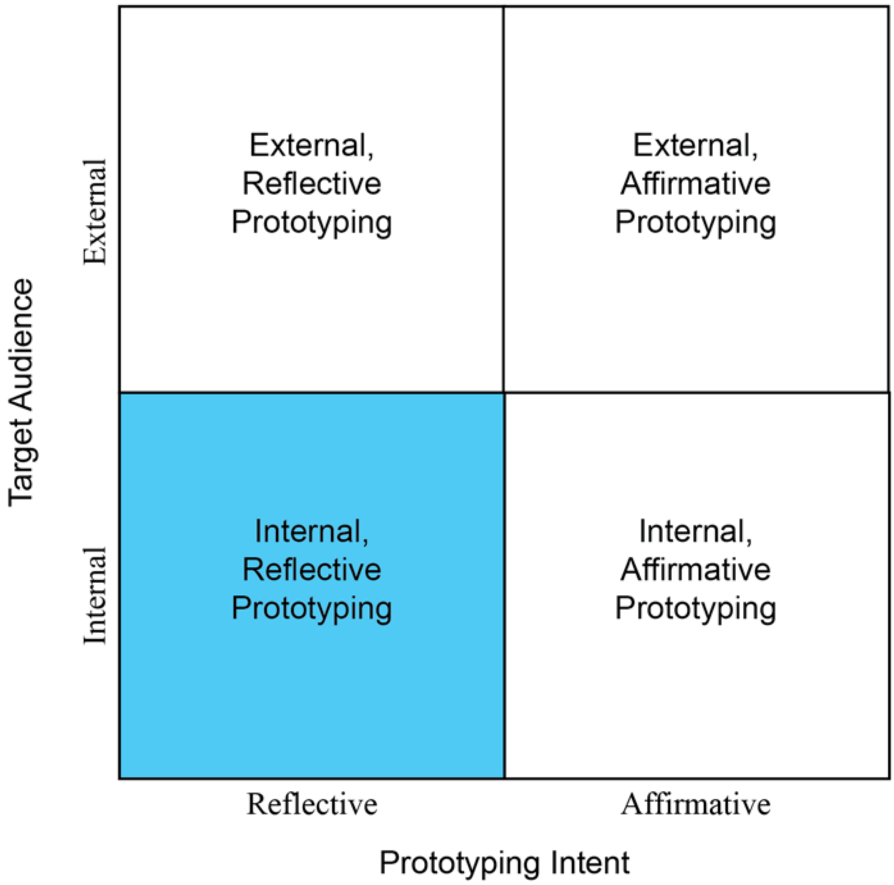

Figure 6 – The Audience-Intent Model, taken from Research Paper III.

One closely related dimension, though not explicitly expressed in this model, is fidelity. As the nature of internal, reflective prototyping implies, it typically involves low fidelity prototyping. Even so, the fidelity level of prototyping is rather to be considered a result of the learning intent and audience of the prototyping. Whether it is tacit knowledge creation, or verification and validation testing.

2.3.3 The Affordance Dimension of Prototyping

In the same way as the term fidelity describes the influence on individual perception of an artefact, the term affordance describes the individual perception of how to interact with an artefact. The term is further outlined in Research Paper II and its significance in knowledge creation and prototyping is further portrayed. As stated by (Norman, 1988): “the term affordance refers to the perceived and actual properties of the thing, primarily those fundamental properties that determine just how the thing could possibly be used”. Thus, distinguishing affordance from semantics. Semantics is the individual interpretation of the meaning of a prototype, while affordance is not subject to, but rather a cause of, meaningful interpretation.

2.3.4 Prototyping as an Explorative Tool in Requirements Elicitation

As shown by Chou & He (2004) the externalization stage of the SECI knowledge creation spiral is facilitated by conceptual knowledge assets (e.g. prototypes). The learning potential in prototyping argued for in the beginning of this chapter, is aimed at creating tacit knowledge. Further, the goal of the reflective prototyping categories is exploration. Thus, we argue that explorative prototyping is enabling the processes 1-3, as shown in the examples presented in the Research Papers I and III, while process 4 is best solved analytically.

The empirical evidence reviewed by Davis et al. (2006) concludes interviews to be the most efficient elicitation method, and also states that “The studies conducted have not found the use of intermediate representations during elicitations to have significant positive effects.” This is concluded to be partly because prototypes induce fixation in the interview subjects. However, the empirical evidence presented regarding prototypes is limited to the use of prototypes during interview sessions (Goodrich & Olfman, 1990; Moore & Shipman, 2000; Engelbrektsson, 2002).

Still, from the study by Moore & Shipman (2000), they conclude that “The process of interface artifact construction allowed end users to express information that a questionnaire failed to elicit.” Hence, the engineer could gain a better initial idea of the available design space. The reviewed literature does not sufficiently cover the unknown unknowns and the explorative benefits of prototyping, and we argue there is an untapped potential in this topic.

2.4 Design Fixation in Prototyping

Design fixation is an effect that appears in design activities when fixation on examples causes an inhibiting effect on the further idea creation. The varying context of design objectives, human activity and field of knowledge causes the definitions of design fixation to differ greatly, as characterized by Moreno, Yang, Hernández, Linsey & Wood (2015). A review by the same authors assess several metrics to evaluate design work, and hence design fixation. These include quality, quantity, novelty (originality), workability (usefulness), relevance, thoroughness (feasibility), variety, and breath. Further, methods for overcoming design fixation is categorized into intrinsic approaches, relying on intuition or personal experience (i.e. tacit knowledge), extrinsic approaches, relying on external stimuli/assistance (i.e. explicit knowledge), and whether it is implemented on an individual or group level.

The use of physical models to mitigate design fixation is investigated by Viswanathan, Atilola, Esposito & Linsey (2014). In their study, made with freshman engineering students, fixation on negative features in presented example models is examined. The initial conditioning was providing an example with negative features, an examples with negative features while conveying a warning of the flaws, or an example with positive features. The work was done in groups in two sessions during a span of one week, the first consisting of an ideation process based on task description and initial examples, and the second on incremental testing and building. The results show that some bad features are depleted by warning, while others are not depleted unless the designers are allowed to test the prototype, indicating the testing and interaction with physical prototypes in some cases cause creation of tacit knowledge even if the same information is explicitly expressed in advance.

As we assert in Research Paper II, there are several effects coming into play when comparing high affordance prototyping (i.e. physical modelling) and low affordance prototyping (i.e. sketching). The assumption made from the available literature entails that less design fixation occurs when doing low affordance prototyping, compared to high affordance prototyping, while testing of physical models (requiring a certain level of affordance) mitigates design fixation. Design fixation studies by Acuna & Sosa (2011) and Viswanathan & Linsey (2013) conclude the involvement of physical models to also aid the participants' construction of mental models, and yield more functional designs. Thus, indicating that high affordance prototypes lead to more design fixation, but also enhanced functionality of the designs.

This coincides with the ‘sunk cost effect’ (Viswanathan & Linsey, 2013), suggesting higher personal investment in a concept by the designer will increase their evaluation of the design, increasing design fixation. Thus, in situations where the designers are not sufficiently invested the assumed correlation between affordance and design fixation may not be present, as is the case in Viswanathan & Linsey (2013) and Youmans (2011), where the “sunk cost effect” is not detected.

Further, Youmans (2011) make an observation regarding the use of groups in ideation work. Compared to using nominal groups (i.e. individuals doing ideation separately and joining their results together), ordinary groups fixated more. The study suggests this is a result of group dynamics, and one or a few group members taking charge and causing the remaining members to fixate on certain concepts. Thus, group dynamics greatly complicates experiments regarding individual creation of tacit knowledge.

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3 Research Experiment Setup

To properly evaluate the problem at hand, we decided to devote some time to designing and running a research experiment on prototype affordance in learning activities. Originally proposed in Research Paper II, the experiment aims to explore the effects of prototype affordance in a product development setting. This section is devoted to elaborating the said research experiment, and highlight some of the areas not elaborated in the previously mentioned research paper.

3.1 Hypotheses

With the problem statement in mind, we aim at exploring how altering prototyping affordance during early stage concept creation may impact the project output. Taking inspiration from various sources, including Viswanathan & Linsey (2013), we propose three main hypotheses, which we are trying to test in our experiment. These hypotheses include; the ‘Problem and Concept Understanding Hypothesis’, the ‘Design Fixation Hypothesis’ and the ‘Learning Activity Hypothesis’.

3.1.1 Problem and Concept Understanding Hypothesis

As explained in Research Paper II, this hypothesis aims at testing the impact of prototype affordance, and how this affects the ability to evaluate different concepts. Slightly modified from its original form, the null hypothesis is stated as follows;

> *Interaction with high affordance prototypes will not lead to different problem and concept understanding (during concept evaluation) than interaction with low affordance prototypes.*

With the corresponding alternative hypothesis stated as follows;

> *Interaction with high affordance prototypes will lead to different problem and concept understanding (during concept evaluation) than interaction with low affordance prototypes.*

We argue that, in order to do a proper and thorough concept evaluation, one needs to understand and learn the properties, limitations and possibilities in both the problem at hand and the concepts that aim at solving this problem. Moreover, we argue that this understanding comes from a mix of previous experience and the ability to learn about the problem and concepts. Hence, this hypothesis aims at testing if prototype affordance may affect the way we learn when trying to understand problems and concepts, and if this may lead to a better (more accurate) concept evaluation.

3.1.2 Design Fixation Hypothesis

As mentioned previously, design fixation can be a major issue in product development. When introducing prototyping affordance in our research experiment, we need to test for any fixation effects that may be induced by adding or removing levels of affordance. In line with current literature, including similar design fixation experiment efforts by Viswanathan et al. (2014), Viswanathan & Linsey (2013) and Youmans (2011) we state the null hypothesis as follows:

> *Interaction with high affordance prototypes will not lead to different levels of design fixation (when designing) than interaction with low affordance prototypes.*

Moreover, the alternative hypothesis is stated as follows:

> *Interaction with high affordance prototypes will lead to different levels of design fixation (when designing) than interaction with low affordance prototypes.*

3.1.3 Learning Activity Hypothesis

Closely linked to the Problem and Concept Understanding Hypothesis, we have the Learning Activity Hypothesis:

> *Interaction with high affordance prototypes will not lead to different quality of designs than interaction with low affordance prototypes.*

Being the null hypothesis, this hypothesis also has an alternative hypothesis;

> *Interaction with high affordance prototypes will lead to different quality of designs than interaction with low affordance prototypes.*

This hypothesis is based on the framework on internal, reflective prototypes (as described in Research Paper II), and the argument that previous learning experience (i.e. the interaction and evaluation of prototypes) can and will be used in new applications and iterations of designs. Here, we are testing if prototype affordance affects the ability to re-iterate on previously designed concepts, as this may be very beneficial in a product development setting.

3.2 Experimental Setup

To further evaluate our hypotheses, we have divided the experiment into a two-part controlled setup (as described in Research Paper II). In this setup, all participants have been randomly assigned to either of two conditions. These conditions; ‘Low Affordance’ and ‘High Affordance’ describe the kind of internal, reflective prototypes that will be presented to – and used by – the participants during the experiment.

We are interested in testing both learning and ability to iterate new concepts. Hence, the experiment is comprised of two subsequent tasks. Upon starting the experiment, each participant is handed a specific technical problem, and the first task is to evaluate pre-made concepts that attempt to solve this problem. As the point of this task is to evaluate concepts, this round will subsequently be referred to as ‘the evaluation round’. The second task is to iterate on these designs, hopefully creating a new concept that is better at solving the technical problem than the pre-made concepts presented in the first task. This second round will subsequently be referred to as ‘the iterative design round’.

This experiment has been designed and intended for automotive engineers, as we are collaborating with Kongsberg Automotive. Therefore, we expect participants to be familiar with concept evaluation and creation. Additionally, we have chosen to also run the experiment with graduate students from mechanical engineering at NTNU, as this gives a foundation for further comparison between the two groups.

3.3 Technical Problem and Pre-made Concepts

In this experiment, we are using a technical problem from Kongsberg Automotive’s current portfolio. This problem is provided from the company’s research and development unit in Kongsberg, and includes designing adjustable clutch actuators for the automotive industry (primarily trucks). In general, clutch actuators are devices for mechanically actuating the clutch, enabling gear change. Albeit simple in theory, there are several factors that complicate the design. In particular, clutches are subject to wear, thus requiring a change in actuation position over time. There are several other complicating factors to consider, and we are only listing *some* of these factors here.

Taking this highly complex problem space into a controlled experiment setup requires some modification, to enable our participants to grasp the problem setting and task within the set time-constraints. As a result, we have phrased the technical problem this way:

> *The technical problem is comprised of a locking mechanism for two wagons, which are mounted on rails. The two wagons are both able to move freely in their own rails, but are prohibited from moving past each other by the locking mechanism. In addition, the locking mechanism is required to lock both wagons into each other in such a way that force can be transferred from the one wagon to the other.*
>
> *This problem is an abstraction of a locking mechanism for a commercial car model. Hence, the system is subject to wear. Because of this, the locking mechanism needs to be adjustable in such a way that the two wagons can lock at different positions.*

This problem text is an abstraction of the real-life problem, and aims to enable participants to solve the task regardless of having previous experience with clutch actuators. Furthermore, the task of the evaluation round was phrased similarly, asking the participants to evaluate four pre-made concepts as solutions to the previously discussed technical problem.

After having spent some time with Kongsberg Automotive, getting to know both methods of the research and development unit and the technical problem, we were introduced to four concepts that Kongsberg Automotive were considering for the given technical problem. These concepts were assessed as possible concepts to further develop for a concentric clutch actuator system. The four concepts were somewhat altered (in agreement with Kongsberg Automotive) to suit the technical problem’s level of complexity.

The four different concepts mentioned have been prototyped and represented in two different levels of affordance. All concepts were initially sketches presented by Kongsberg Automotive that we adopted, modified and prototyped with an anodized aluminum prototyping kit by MakeBlock™. The concepts were subject to several iteration-cycles before being finalized, and ultimately these aluminum prototypes were the high affordance prototypes presented to half of the participants. The physical concepts were then transferred into CAD-software, and technical drawings of the concepts were made and printed on A3 paper. These drawings (including multiple views of each concept) were the 'low affordance' prototypes presented to the last half of the participants, and the physical concepts were their 'high affordance' prototype equivalents. Both representations of Concept A are displayed in Figure 7, Concept B in Figure 8, Concept C in Figure 9 and Concept D in Figure 10.

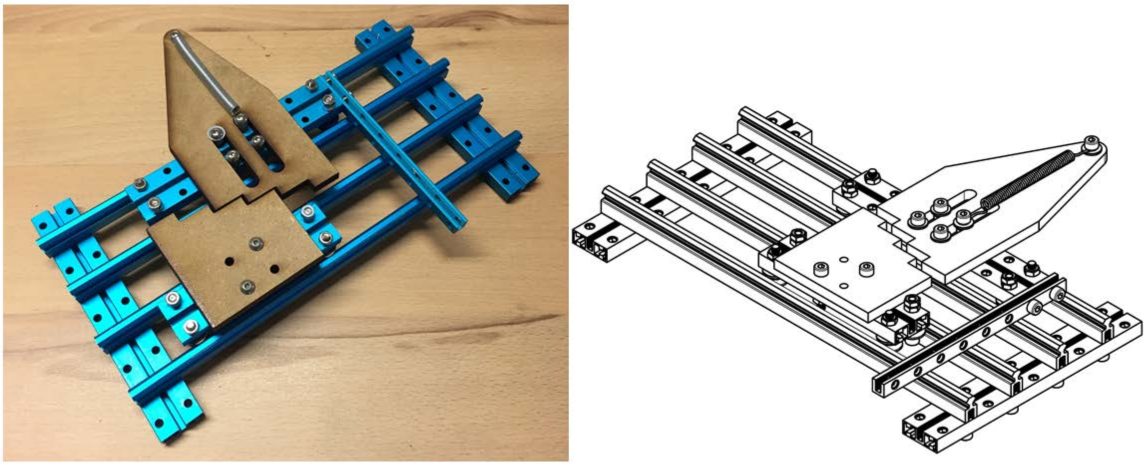

Figure 7 – High and low affordance representations of Concept A. The 'low affordance representation' includes several views of the same technical drawing, all in 1:1 scale.

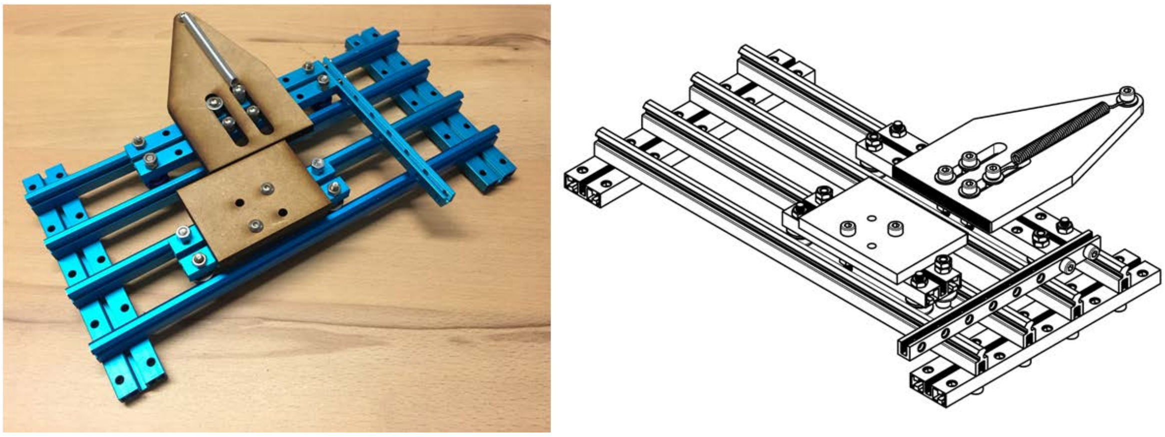

Figure 8 – High and low affordance representations of Concept B. The 'low affordance representation' includes several views of the same technical drawing, all in 1:1 scale.

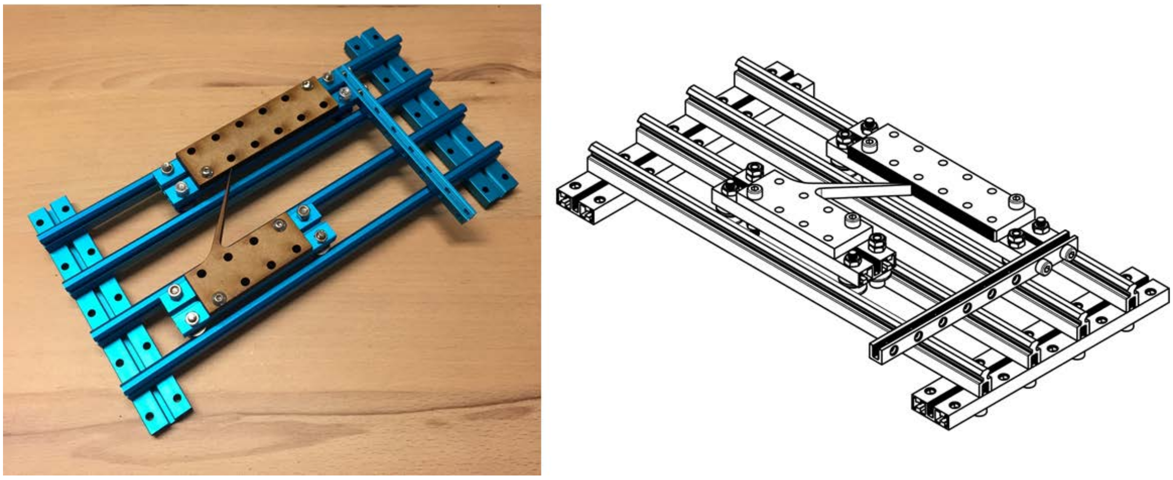

Figure 9 – High and low affordance representations of Concept C. The 'low affordance representation' includes several views of the same technical drawing, all in 1:1 scale.

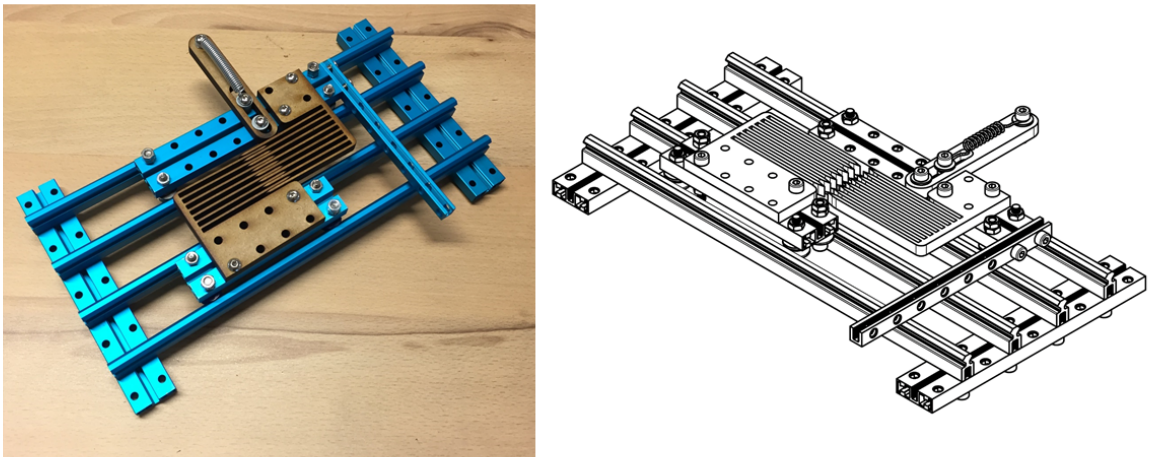

Figure 10 – High and low affordance representations of Concept D. The 'low affordance representation' includes several views of the same technical drawing, all in 1:1 scale.

3.4 Tools, Equipment and Materials

To minimize outside input and biases, all participants were set to do the experiment individually. In addition, one experiment facilitator provided the necessary materials throughout two rounds, including handing out written assignment texts.

Upon starting the experiment, each participant was greeted by the experiment facilitator, and guided to a medium-sized meeting room. Each participant was presented with a handout of papers, including a consent form, an assignment text for the evaluation round and a set of four different pre-made concepts, presented in prototypes whose affordance level match their starting condition (i.e. high or low affordance). In addition, a set of two ball-point pens, a black A3-sized deliverables-folder, a ruler and a stack of blank, A3 printer paper was placed on the meeting room table, as displayed in Figure 11.

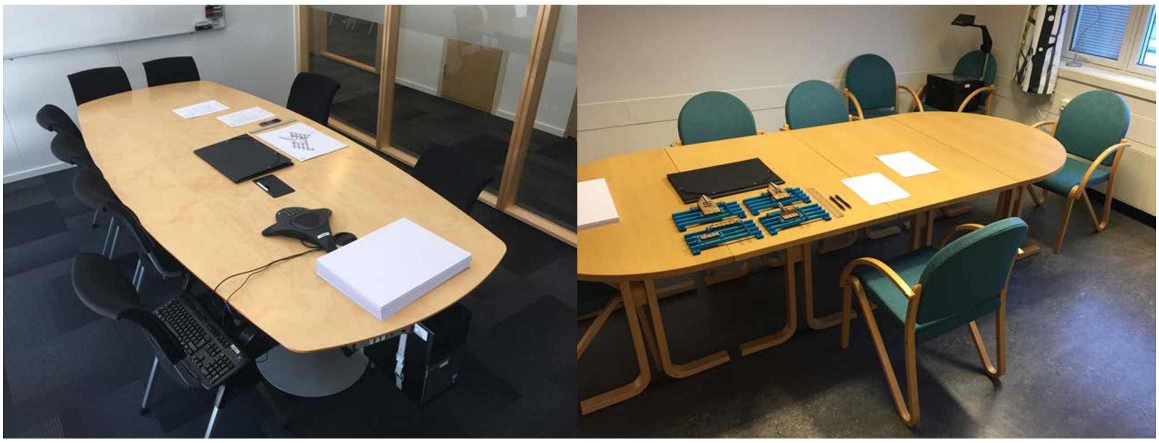

Figure 11 – Experiment setup at Kongsberg Automotive (left) and NTNU (right).

For the iterative design round, another assignment text was provided by the experiment facilitator, along with some ‘blank technical drawings’ (Figure 12). The participant handouts can be found in Appendix A.

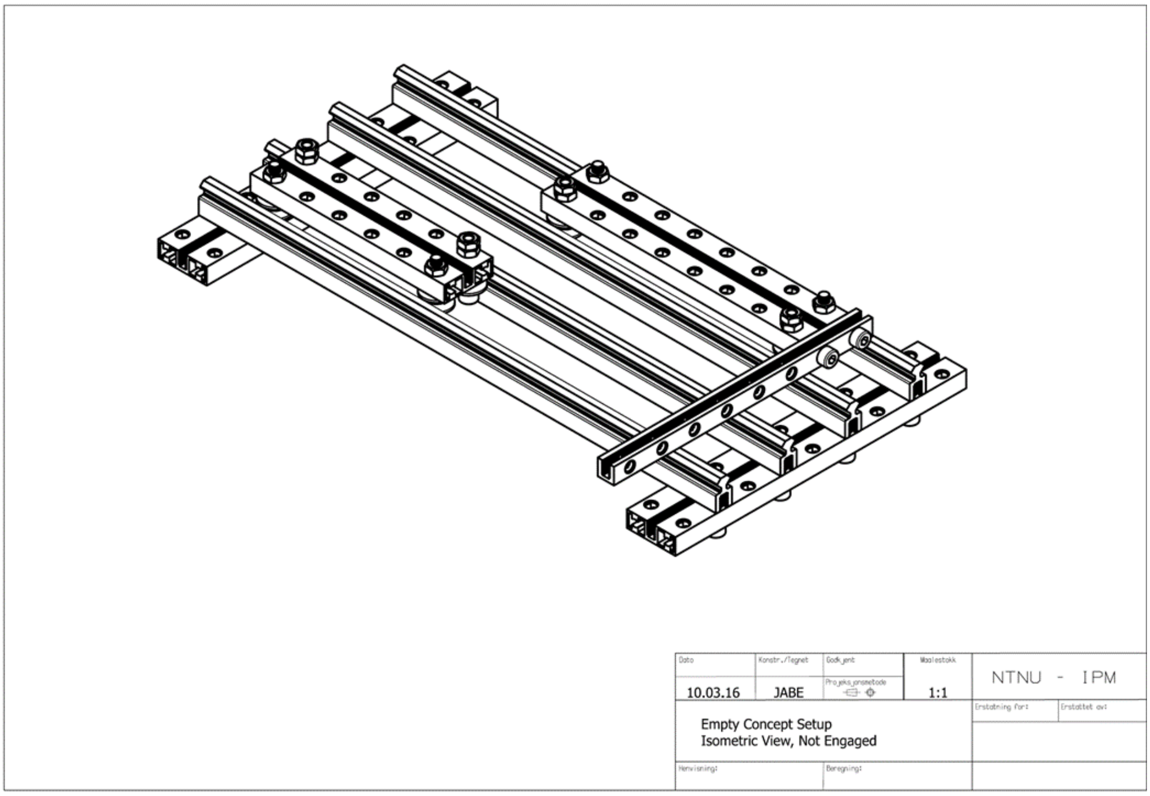

Figure 12 – Example of a blank technical drawing. Four views were included in this handout; disengaged top view, disengaged isometric view, engaged top view and engaged isometric view.

3.5 Experiment Procedure

The experiment was conducted partly at Kongsberg Automotive’s Headquarters in Kongsberg, and partly at NTNU in Trondheim (Figure 11). Upon arrival, each participant was greeted by an experiment facilitator, and asked to fill out the consent waiver, stating full voluntary participation in the experiment. Thereafter, each participant was informed that the experiment was divided in two 20 minute rounds, before being told to start on the task at hand.

3.5.1 Evaluation Round

In the evaluation round, each participant was given 20 minutes, and the task of evaluating the four pre-made concepts based on the prototypes presented. The evaluation was done by giving a ranking of 0 through 10 for each of six pre-defined attributes, asking the participants to fill out an empty evaluation matrix supplied in the participant handout. The attributes were ‘interface friction’, ‘holding force’, ‘disengaging force’, ‘stability’ and ‘complexity’. Additionally, the participants were asked if the presence of each attribute was a negative or positive factor (i.e. weigh each attribute) for solving the technical problem. This weighting was done by filling in a Likert scale (with 7 possible ratings) for each attribute. Upon completion of the evaluation round, each participant was asked to place the completed evaluation matrix and Likert scale sheet in the deliverables-folder.

3.5.2 Iterative Design Round

After completing the evaluation round, participants were given the task description for the iterative design round, and another 20 minutes to finish the task. In this task, participants were asked to iterate on the designs presented, and to deliver one final solution that were supposed to provide a better solution to the technical problem. Upon completion, each participant was asked to do a questionnaire, mapping some previous experience, educations and select demographic data (also found in Appendix A).

Contrasting to statements made in Research Paper II, the iterative design task was limited to drawing and sketching due to time-constraints and to simplify the experiment setup. This made the task more homogenous for the two conditions, and gives a more even foundation for evaluating results.

3.6 Metrics for Evaluation of Hypotheses

To properly evaluate our three stated hypotheses, we needed metrics for this evaluation. This section is devoted to said metrics, including both definition and quantification of all variables. We are using expert opinion ratings in this experiment, similar to the works of (Viswanathan & Linsey, 2013; Youmans, 2011).

3.6.1 Independent Variables

As explained in Research Paper II, prototyping affordance is set as the independent variable for all three hypotheses. We refrain from quantifying this beyond stating that we are using high and low levels of affordance. Hence, the variable is categorical, with two discrete conditions. The independent variable is the level of affordance being used. Although we differentiate between high/low affordance prototyping (i.e. activities) and high/low affordance prototypes (i.e. objects), we view this as the same variable for all practical purposes.

3.6.2 Dependent Variables

The problem and concept understanding hypotheses includes two dependent variables; ‘problem understanding’ and ‘concept understanding’. To determine these variables, we used the participants’ answers from the evaluation round. These answers were compared to a set of pre-defined expert rankings. By comparing the values of the evaluation matrix from the evaluation round to a pre-defined expert ranking (Table 1), we got the concept understanding variable. The pre-defined expert evaluation was made by us, the authors, as we had spent a substantial amount of time examining the technical problem and experiment setup. The problem understanding variable was done in a similar way, by comparing the participants’ Likert scale answers (weighting) with those of the experts (Figure 13). This way, we could assess which of the two conditions (high affordance and low affordance) was closest to the experts’ scores, and thus which one was more correct.

Table 1 – Expert opinion on rankings of concepts A through D.

Physical Attributes	Concept A	Concept B	Concept C	Concept D
Interface Friction	0	6	4	10
Holding Force	10	7	6	3
Disengaging Force	5	3	7	1
Stability	8	6	3	3
Complexity	4	2	6	8

For evaluating the design fixation hypothesis, we used our own mapping of pre-defined fixation features. Prior to running the experiment, several fixation features had been determined by using the pre-made concept prototypes. Each participant’s answer from the iterative design round was then evaluated and categorized by the number of pre-defined design fixation features present in the new designs, giving a sum of fixation features per participant. If the participants had handed in two or more concepts (which some did), the sum of fixation features is measured by taking the average of the fixation features present in the different concepts. In this hypothesis, the dependent variable is the ‘sum of fixation features present’.

	Very Negative	Negative	Slightly Negative	Neutral	Slightly Positive	Positive	Very Positive
Interface Friction	☐	☐	☑	☐	☐	☐	☐
Holding Force	☐	☐	☐	☐	☐	☐	☑
Disengaging Force	☑	☐	☐	☐	☐	☐	☐
Stability	☐	☐	☐	☐	☐	☐	☑
Complexity	☐	☑	☐	☐	☐	☐	☐

Figure 13 – Expert opinion on Likert scale weightings.

To evaluate the learning activity hypothesis, we used ‘quality of design’ as our dependent variable. To get a value for this variable, we started by using the evaluation matrix (i.e. the same as used by the participants in the evaluation round) for an expert ranking of each participant’s answers. Again, if a participant had handed in two or more concepts, the average of these concepts was used as this participant’s ranking. Furthermore, these rankings (Table 1) were combined with the expert weighting (Figure 13) to produce a combined ‘quality of design’ metric, giving an indication of whether the deviation is positive (better) or negative (worse). This metric is calculated using Equation (1):

$$Quality\ of\ Design = \sum_{i=1}^{n=5} 'attribute\ weighting' * 'attribute\ presence\ rank' \qquad (1)$$

For example, if we were to rank the pre-made ‘Concept A’ this way, using the expert opinion rankings of Table 1 and weightings of Figure 13, we would get the score shown in Equation (2):

$$\begin{aligned} &Quality\ of\ Design \\ &= (-1) * (0) + (3) * (10) + (-3) * (5) + (3) * (8) + (-2) * (4) \\ &= 0 + 30 - 15 + 24 - 8 \\ &= 31 \end{aligned} \qquad (2)$$

3.6.3 Statistical Evaluation Procedure

To statistically evaluate our hypotheses, we used independent samples t-tests (often referred to as ‘Student T-tests’) in SPSS Statistics™ by IBM. This test makes six assumptions, and understanding these are key to understanding both the validity and robustness of our results. The first assumption is that we have one dependent variable that is measured on a scale (i.e. is a ‘continuous variable’), and the second is that we have an independent variable with two independent groups (i.e. ‘categorical independent groups’). The third assumption is that we have independence of observations, meaning that we have no relationship between the groups or independent variable. Furthermore, the fifth assumption states that there *should* not be any significant outliers within either of the two groups (of the independent variable). Outliers can be categorized in three categories; ‘data entry errors’, ‘measurement errors’ and ‘genuinely unusual values’. It may be necessary to keep outliers, as removing ‘genuinely unusual values’ then may result in creating misleading (or even false) results, as we explain in Appendix D. Consequently, we aim at keeping outliers in our data, as long as we do not have sufficient evidence that the outliers are either ‘data entry errors’ or ‘measurement errors’. Assumption five is that the dependent variable is normally distributed for each group of the independent variable. This can be checked through a Shapiro-Wilk test, giving a significance test for each distribution – where significant ($p < .05$) results indicate a violation of the assumption of normality. The sixth – and last – assumption is that we have homogeneity of variances. This means that the two groups’ variances must be equal, as the required t-test will vary if this homogeneity is violated or not. SPSS Statistics™ uses ‘Levene’s Test of Equality of Variances’ to test for this homogeneity, which is incorporated directly into the independent samples t-test. SPSS Statistics™ outputs two different t-tests for both cases (homogeneity and heterogeneity), which is used in tandem with ‘Levene’s Test of Equality of Variances’.

Additionally, we test the significance level of this equality of variances, testing if the variances are *statistically significant* ($p < .05$), and possibly *highly significant* ($p < .01$). The second test is a t-test for equality of means, testing whether the means are significantly different. The tabular data from the second test outputs two rows of data, which are dependent on the first significance level; if the variances are significantly different, we use (and read) the row labeled ‘Equal variances assumed’, and if the variances are not significantly different, we use the row labeled ‘Equal variances not assumed’.

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4 Research Experiment Results

In this section, results gathered from the previously presented research experiment are presented, analyzed and discussed in detail. The section first introduces statistical results, before evaluation of hypothesis is elaborated. In this thesis, we have chosen to focus our efforts in analyzing the data from the full 33 participant dataset. However, we are also including analyses from various sub-sets of data – all of which are located in Appendix C. In addition, we have chosen to include an example on the impact of removing outliers from our data, which can be found in Appendix D.

A total of 41 participants have participated in this study. Of these, 11 have been professional engineers from Kongsberg Automotive, and 30 have been graduate students from mechanical engineering at NTNU. Due to various reasons, some participants have chosen to abort their participation before the experiment time had expired, resulting in the loss of some data points. Consequently, we are left with a total of 33 full data-sets, of which 9 were Kongsberg Automotive employees, and 24 were graduate students from NTNU. Of these 33 participants, 16 were given the 'low affordance' prototypes (i.e. technical drawings), and 17 were given the 'high affordance' prototypes (i.e. physical models). The 11 subjects that participated from Kongsberg Automotive did so on March 14th through 18th (of 2016) in Kongsberg. The 30 subjects that participated from NTNU did so on April 4th through 8th (of 2016) at NTNU. A total of 11 of the student participants were female, and 13 were male. All of the 9 participants from Kongsberg Automotive were male. The 33 participants were distributed across several nationalities, including French (3 participants), Italian (1 participant), German (1 participant), Swedish (1 participant), Slovak (1 participant), Israeli (1 participant), Finnish (2 participant) and Norwegian (23 participants).

4.1 Statistical Analyses

During the experiment, answers from each participant were collected and stored for review. These answers were then analyzed using SPSS Statistics™ by IBM, using the whole population (N = 33) of participants.

4.1.1 The Evaluation Round

In the evaluation round, each participant used 20 minutes to produce an evaluation matrix for evaluating each of the four pre-made concepts, together with a Likert scale questionnaire on how the presence of different attributes would affect the technical problem. The values inserted in the evaluation matrix (Table 1) is referred to as ‘rankings’, and the Likert scale questionnaire (Figure 13) answers are referred to as ‘weightings’ in this section.

The testing of the Problem and Concept Understanding Hypothesis is twofold, as we have separated problem understanding and concept understanding from each other. For testing problem understanding, we used affordance as the independent variable, and the five different attribute weightings as dependent variables. For the evaluation of concept understanding, we used affordance as the independent variable, and all the rankings of Concept A through D (to a total of 20 rankings, 5 per concept). Evaluation of both problem understanding and concept understanding was done by using an independent samples T-test, meaning that we also need to test for outliers, normality and between-group variability, before comparing means (as explained in section 3.6.3).

4.1.1.1 Independent Samples T-test on Problem Understanding

When weighting the attributes, the participant gave values for each attribute on a Likert scale ranging from -3 to +3, and the distributions are displayed in Figure 14. Before continuing with the independent samples t-test, we need to examine the descriptive results for outliers and normality.

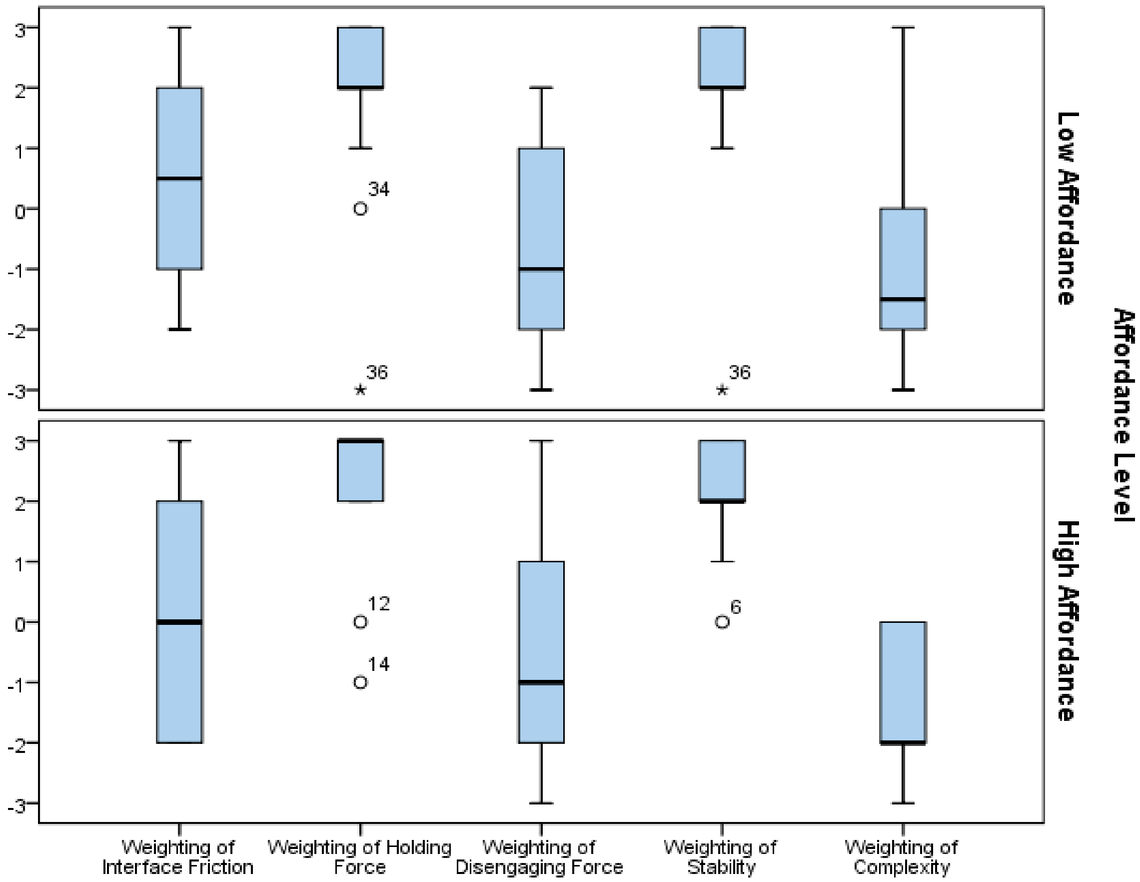

Figure 14 - Boxplot of participants' weightings of attributes. Mild outliers are marked by circles, and extreme outliers are marked with a star, both with unique participant IDs. The bold middle line is the group median.

In Figure 14, we see that we have four outliers in the 'weighting of holding force' category (Participant IDs 12, 14, 34 and 36), and two outliers in the 'weighting of stability' category (Participant IDs 6 and 36). These outliers *could* be considered as 'data entry errors', but as we do not have sufficient evidence to evict the outliers, we accept them as genuinely unusual values (as described in Appendix D). Furthermore, when we consider the normality of distributions, there are several distributions that are not normally distributed (as shown in Appendix C). However, as the group sizes are quite similar, and the independent samples t-test is quite robust, we continue by doing the t-test anyway.

Results from the independent samples t-test are displayed in Table 2. Here, the 'Levene's Test for Equality of Variances' shows that all the distributions are homogenous, and there are no significant differences ($p < .05$) between the means of the two conditions. However, we see thatin 'weighting of interface friction', the low affordance (M = .50, SD = 1.592) varies slightly less than the high affordance (M = .12, SD = 1.965) condition.

Table 2 - Independent samples t-test on problem understanding. Non-significant results are highlighted in grey.

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference Lower	Upper
Weighting of Interface Friction	Equal variances assumed	2,488	,125	,612	31	,545	,382	,625	-,892	1,657
	Equal variances not assumed			,616	30,351	,543	,382	,621	-,885	1,650
Weighting of Holding Force	Equal variances assumed	,225	,638	-,625	31	,537	-,298	,476	-1,269	,674
	Equal variances not assumed			-,619	27,389	,541	-,298	,481	-1,284	,688
Weighting of Disengaging Force	Equal variances assumed	,075	,786	,425	31	,674	,265	,623	-1,005	1,535
	Equal variances not assumed			,425	30,874	,674	,265	,623	-1,005	1,535
Weighting of Stability	Equal variances assumed	,350	,558	-,416	31	,680	-,173	,415	-1,019	,674
	Equal variances not assumed			-,410	23,288	,686	-,173	,422	-1,045	,699
Weighting of Complexity	Equal variances assumed	,908	,348	,599	31	,553	,294	,491	-,707	1,295
	Equal variances not assumed			,592	25,767	,559	,294	,497	-,727	1,316

4.1.1.2 Independent Samples T-tests on Concept understanding

When ranking the concepts, each participant gave a ranking on a scale from 0 through 10 on each attribute, using an evaluation matrix. The tests for concept understanding, include 20 different rankings (i.e. separate dependent variables), and thus get 20 different t-tests. To increase readability, we have divided these 20 t-tests into groups of five, sorted by their respective concept (A through D). A summary of the concept rankings, along with full frequency tables for all rankings can be found in Appendix C.

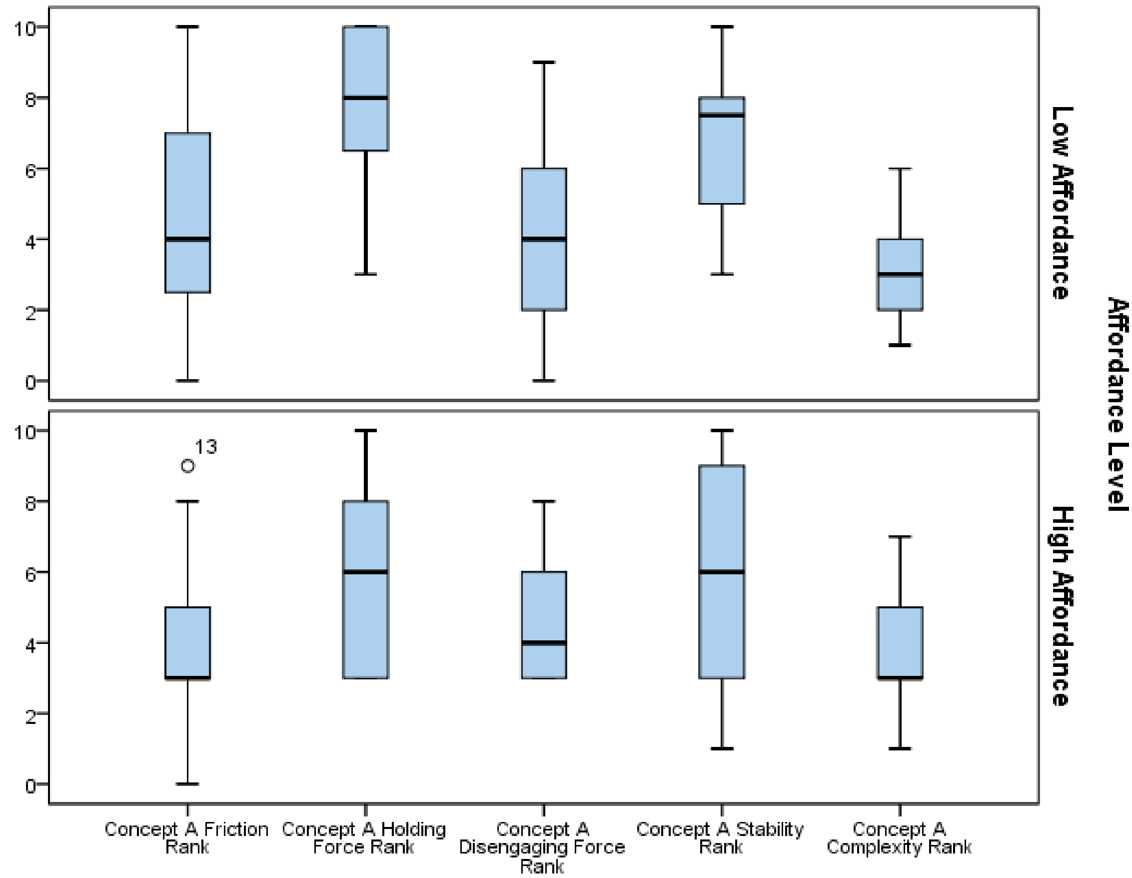

Figure 15 - Boxplot of the participants' rankings of Concept A. The mild outlier is marked by a circle, with a unique participant ID.

The distributions of Concept A (Figure 7) rankings are displayed in Figure 15. Here, we see larger difference between 'low affordance' and 'high affordance', especially when ranking holding force, where participants using low affordance (M = 7.81, SD = 2.316) gives slightly higher ranks than those using high affordance (M = 6.00, SD = 2.622). It is worth noting that the whole scale of 0 through 10 has been used by the participants using 'low affordance' prototypes for ranking friction in Concept A. In Figure 15, we see one outlier (being participant ID number '13'). As with the previous test, we cannot identify this outlier as anything else than a genuinely unusual value, and hence accept the outlier in our data. When checking for normality of the distributions, there are three distributions violating the assumption of normality (as shown in Appendix C). However, the groups are similar in size, meaning that the t-test should not be significantly altered by this skewness.

Table 3 - Independent samples t-test on concept understanding for Concept A. The significant result is highlighted in yellow, and non-significant results are highlighted in grey.

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Concept A Friction Rank	Equal variances assumed	,520	,476	,646	31	,523	,618	,956	-1,333	2,568
	Equal variances not assumed			,643	29,739	,525	,618	,961	-1,345	2,581
Concept A Holding Force Rank	Equal variances assumed	,289	,594	2,099	31	,044	1,813	,863	,052	3,573
	Equal variances not assumed			2,108	30,884	,043	1,813	,860	,058	3,567
Concept A Disengaging Force Rank	Equal variances assumed	1,630	,211	-,351	31	,728	-,276	,785	-1,877	1,326
	Equal variances not assumed			-,347	26,710	,731	-,276	,794	-1,905	1,354
Concept A Stability Rank	Equal variances assumed	4,162	,050	1,043	31	,305	,926	,888	-,885	2,737
	Equal variances not assumed			1,057	27,618	,300	,926	,877	-,871	2,723
Concept A Complexity Rank	Equal variances assumed	1,710	,201	-,608	31	,548	-,338	,556	-1,473	,797
	Equal variances not assumed			-,613	29,468	,544	-,338	,551	-1,465	,789

In Table 3, we observe that the means of the low affordance condition was 1.813, 95% CI [0.052 to 3.573] higher than the means of the high affordance condition, giving us a significant difference in ranking of ‘holding force’ for Concept A between the two conditions, $t(31) = 2.099$, $p = .044$. Comparing this to the expert ranking (with the value of 10) in Table 1, we observe the low affordance condition being closer to the expert ranking than the high affordance condition.

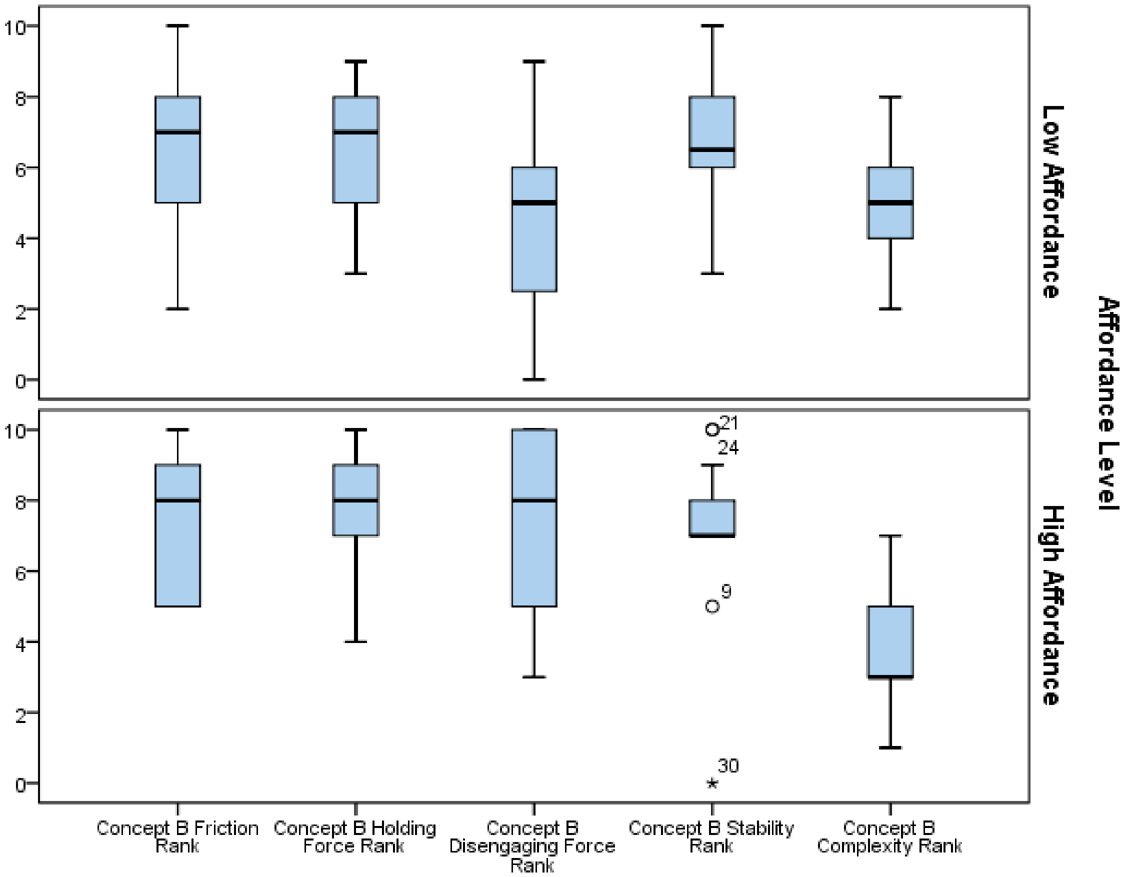

Figure 16 - Boxplot of the participants' rankings of Concept B. Mild outliers are marked by circles, and extreme outliers are marked with a star, both with unique participant IDs.

Moving on, the distributions of Concept B (Figure 8) rankings are visualized in Figure 16. Here, we see pronounced differences between the two affordance levels across multiple rankings. However, by examining the dataset, we also see that the ranking of stability contains four outliers in the high affordance condition (Participant IDs 9, 21, 24 and 30). Again, as we cannot conclude that these are not genuinely unusual values, we accept them as outliers in our data. When examining the normal distributions, we discover that three of the distributions are not normally distributed, all belonging to the high affordance condition (being 'interface friction' (M = 7.35, SD = 1.801), 'disengaging force' (M = 7.41, SD = 2.623) and 'stability' (M = 7.29, SD = 2.257), as shown in Appendix C). As the distributions are either similarly sized and/or skewed in the same direction, we continue with the t-test.

In Table 4, the results from the t-tests of Concept B rankings are displayed. As seen here, the participants from the low affordance condition (M = 4.56, SD = 2.555) have ranked the 'disengaging force' of Concept B as 2.849, 95% CI [1.009 to 4.690] lower than the participants from the high affordance condition (M = 7.41, SD = 2.623). It is worth noting that this result is statistically highly significant, *t(31) = -3.158, p = .004*. Additionally, we observe that all the distributions have passed the 'Levene's Test for Equality of Variances', maintaining homogeneity of variances. If we compare the two conditions' mean values to the expert ranking of Table 1, we see that the low affordance condition is closer to the expert ranking (with the value of 3).

Table 4 - Independent samples t-test on concept understanding for Concept B. The significant result is highlighted in yellow, and non-significant results are highlighted in grey.

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Concept B Friction Rank	Equal variances assumed	,812	,374	-1,451	31	,157	-1,040	,717	-2,503	,422
	Equal variances not assumed			-1,440	28,421	,161	-1,040	,722	-2,519	,438
Concept B Holding Force Rank	Equal variances assumed	,188	,668	-1,734	31	,093	-1,081	,623	-2,352	,190
	Equal variances not assumed			-1,732	30,711	,093	-1,081	,624	-2,354	,192
Concept B Disengaging Force Rank	Equal variances assumed	,014	,906	-3,158	31	,004	-2,849	,902	-4,690	-1,009
	Equal variances not assumed			-3,160	30,959	,004	-2,849	,902	-4,688	-1,010
Concept B Stability Rank	Equal variances assumed	,018	,894	-,854	31	,400	-,607	,710	-2,056	,842
	Equal variances not assumed			-,860	30,098	,397	-,607	,705	-2,047	,834
Concept B Complexity Rank	Equal variances assumed	1,338	,256	1,493	31	,146	,875	,586	-,320	2,070
	Equal variances not assumed			1,500	30,740	,144	,875	,583	-,315	2,065

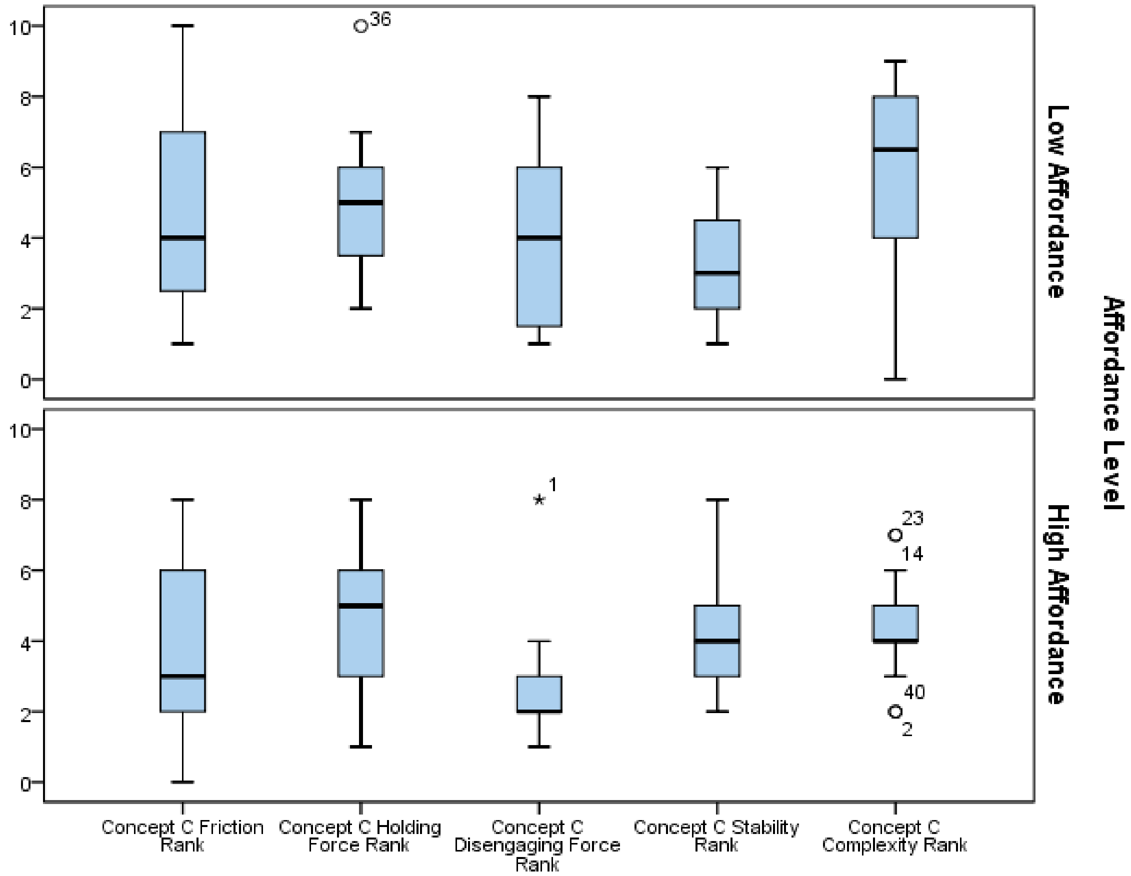

Figure 17 - Boxplot of the participants' rankings of Concept C. Mild outliers are marked by circles, and extreme outliers are marked with a star, both with unique participant IDs.

Figure 17 shows the distributions of rankings of Concept C (Figure 9). In this figure, we see that we have outliers in the 'holding force' (Participant ID 36), 'disengaging force' (Participant ID 1) and 'complexity rankings' (Participant IDs 2, 14, 23 and 40). Similar to the previous results, we accept these outliers as we cannot identify them as not being genuinely unusual values. Note that all attributes, except 'stability', are ranked higher by those subject to the low affordance condition. There are only two distributions that violate the assumption of normality, these being both high ($M = 2.65$, $SD = 1.579$) and low ($M = 3.94$, $SD = 2.620$) affordance rankings of 'disengaging force', continue the t-test nonetheless.

In Table 5, we see the results from the independent t-tests on concept understanding for Concept C. Not surprisingly, after examining the distributions of 'disengaging force' in Figure 17, we see that 'disengaging force' has violated the homogeneity of variances in Levene's test. Moreover, we see that there are no significant results in the t-tests, meaning that none of the conditions' rankings of Concept C are significantly different.

Table 5 - Independent samples t-test on concept understanding for Concept C. Naon-significant results are highlighted in grey.

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Concept C Friction Rank	Equal variances assumed	1,039	,316	1,341	31	,190	1,210	,902	-,630	3,049
	Equal variances not assumed			1,334	29,465	,192	1,210	,907	-,643	3,062
Concept C Holding Force Rank	Equal variances assumed	,133	,718	,476	31	,638	,338	,711	-1,112	1,788
	Equal variances not assumed			,475	30,683	,638	,338	,712	-1,114	1,790
Concept C Disengaging Force Rank	Equal variances assumed	5,136	,031	1,726	31	,094	1,290	,748	-,234	2,815
	Equal variances not assumed			1,701	24,342	,102	1,290	,759	-,274	2,855
Concept C Stability Rank	Equal variances assumed	,166	,686	-1,435	31	,161	-,798	,556	-1,932	,336
	Equal variances not assumed			-1,433	30,656	,162	-,798	,557	-1,934	,338
Concept C Complexity Rank	Equal variances assumed	8,190	,007	1,395	31	,173	1,033	,741	-,478	2,544
	Equal variances not assumed			1,372	23,019	,183	1,033	,753	-,525	2,591

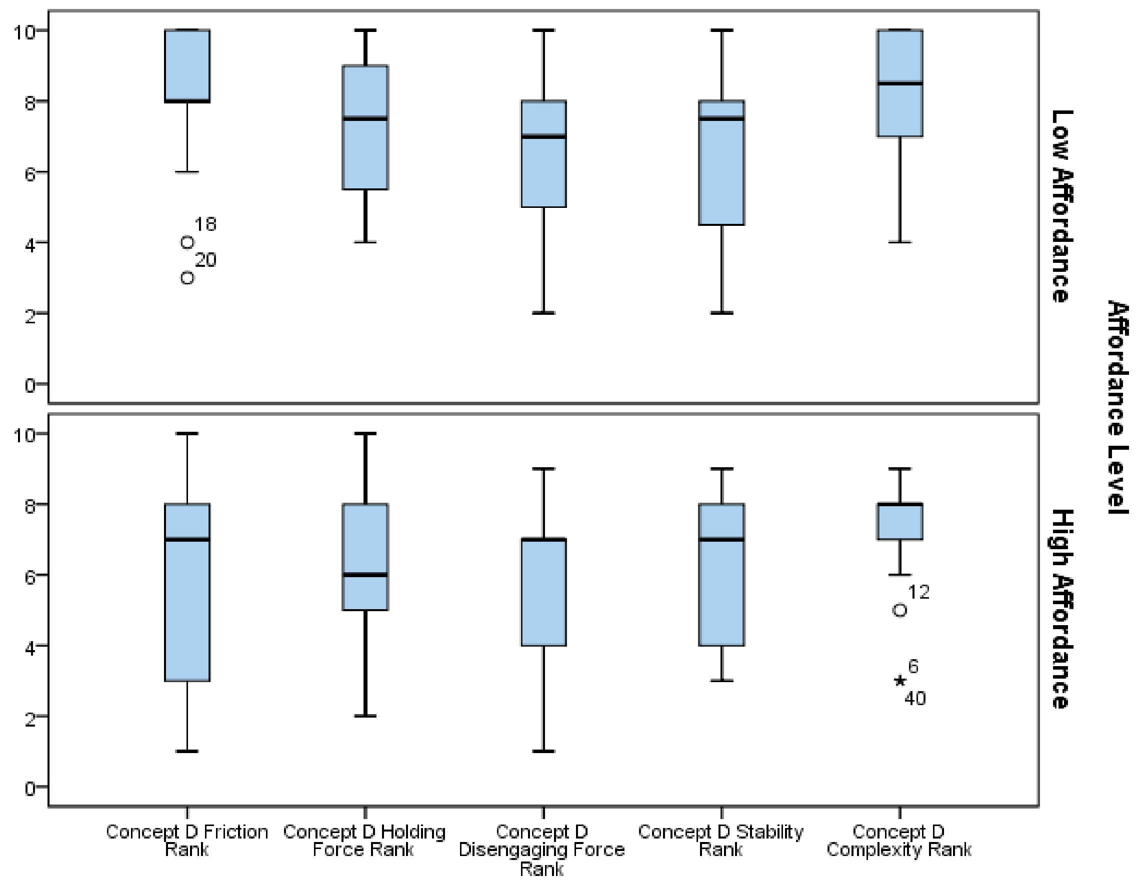

Figure 18 - Boxplot of the participants' rankings of Concept D. Mild outliers are marked by circles, and extreme outliers are marked with a star, both with unique participant IDs.

Lastly, we see the results from all participants' rankings of Concept D (Figure 10) in Figure 18. Here, all attribute means are set higher by those subject to the 'low affordance' condition. Also, note the somewhat large difference in ranking of 'interface friction' for low (M = 8.13, SD = 2.156) and high (M = 5.65, SD = 3.101) levels of affordance. There are two rankings that include outliers, these being 'interface friction' (Participant IDs 18 and 20) and 'complexity' (Participant IDs 6, 12 and 40). Although some participant IDs are repeatedly observed as being outliers (e.g. Participant ID 40 in both 'Concept C Complexity Rank' and 'Concept D Complexity Rank'), we cannot state these are not genuinely unusual values (i.e. a sincere, albeit unusual, estimate by Participant ID 40) and thus accept the outliers in our data. Additionally, we observe several of the distributions to not be normally distributed, but (as previously explained) continue the t-test, disregarding the violation of the assumption of normality.

The results from the independent samples t-tests for Concept D are displayed in Table 6. Also apparent from Figure 18, we see a significant difference in the ranking of ‘interface friction’ by the high affordance and low affordance conditions, $t(28.608) = 2.678$, $p = .012$. The participants from the low affordance condition have ranked the interface friction to be 2.478, 95% CI [0.584 to 4.372] higher than the participants from the high affordance condition. Comparing this to the expert ranking in Table 1, we also see that the low affordance condition is closer to the expert ranking (with a value of 10) than the high affordance condition.

Table 6 - Independent samples t-test on concept understanding for Concept D. The significant result is highlighted in yellow, and non-significant results are highlighted in grey.

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Concept D Friction Rank	Equal variances assumed	6,195	,018	2,649	31	,013	2,478	,936	,570	4,386
	Equal variances not assumed			2,678	28,608	,012	2,478	,925	,584	4,372
Concept D Holding Force Rank	Equal variances assumed	,473	,497	1,354	31	,186	1,022	,755	-,518	2,562
	Equal variances not assumed			1,361	30,602	,183	1,022	,751	-,510	2,554
Concept D Disengaging Force Rank	Equal variances assumed	,410	,527	1,068	31	,294	,919	,861	-,836	2,674
	Equal variances not assumed			1,070	31,000	,293	,919	,859	-,833	2,671
Concept D Stability Rank	Equal variances assumed	,244	,625	,655	31	,517	,504	,768	-1,064	2,071
	Equal variances not assumed			,653	29,735	,519	,504	,772	-1,073	2,081
Concept D Complexity Rank	Equal variances assumed	,282	,599	1,289	31	,207	,882	,685	-,514	2,279
	Equal variances not assumed			1,286	30,485	,208	,882	,686	-,518	2,283

4.1.2 The Iterative Design Round

During the iterative design round, answers from all participants were collected and studied in order to provide an expert evaluation of the re-iterated designs. Each participant had gotten 20 minutes for the iterative design round. The expert evaluation was then used to generate both the 'design fixation' and 'quality of design' metrics.

4.1.2.1 Independent Samples T-test for Testing Design Fixation

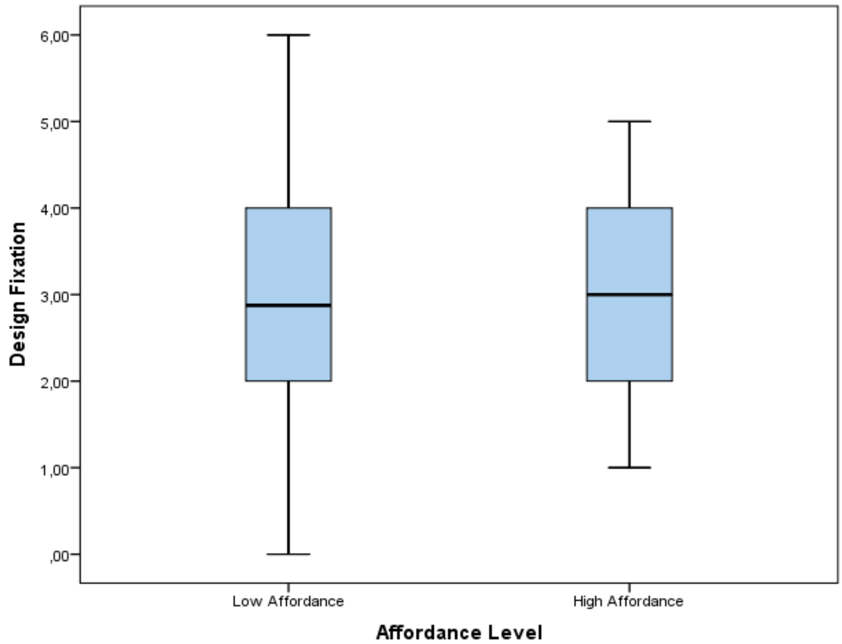

Figure 19 - Boxplot of the distribution of participants' design fixation.

By using expert evaluation, each participant's concept was rated based on a number of pre-defined fixation criteria. As there were 11 fixation criteria in total, each participant's concept would score on a scale from 0 to 11. In Figure 19, the distribution of the design fixation metric is displayed. Here, we see that the low affordance condition (M = 2.94, SD = 1.807) scores similar to the high affordance (M = 3.07, SD = 1.304) condition. However, it is worth noting the larger range of low affordance fixation, also shown by the larger standard deviation. There are no outliers in these distributions, and both distributions are normally distributed (as shown in Appendix C).

The design fixation hypothesis was tested by using an independent samples T-test, with affordance level as our independent variable, the previously described design fixation metric as our dependent variable. Table 7 shows that there is no significant difference between the mean values of the two conditions, $t(31) = -0.240$, $p = .812$. Hence, we see that there is no statistical evidence to say that one condition is performing differently from the other when examining design fixation.

Table 7 - Independent samples t-test on design fixation. The non-significant result is highlighted in grey.

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference: Lower	95% Confidence Interval of the Difference: Upper
Design Fixation	Equal variances assumed	,961	,335	-,240	31	,812	-,13082	,54601	-1,24441	,98277
	Equal variances not assumed			-,237	27,193	,814	-,13082	,55141	-1,26184	1,00020

4.1.2.2 Independent Samples T-test for Testing Quality of Design

Each participant's concept was also subject to an expert evaluation, using the same pre-defined categories as presented in Figure 13. Theoretical maximum for the quality of design metric is +60, and theoretical minimum is -60. The actual distributions are well within this range, as seen in Figure 20. Upon comparing the two conditions, we see a slightly higher mean and median for the low affordance condition (M = 9.60, SD = 13.344) than for the high affordance condition (M = 5.28, SD = 14.354). There are four outliers in Figure 20 –

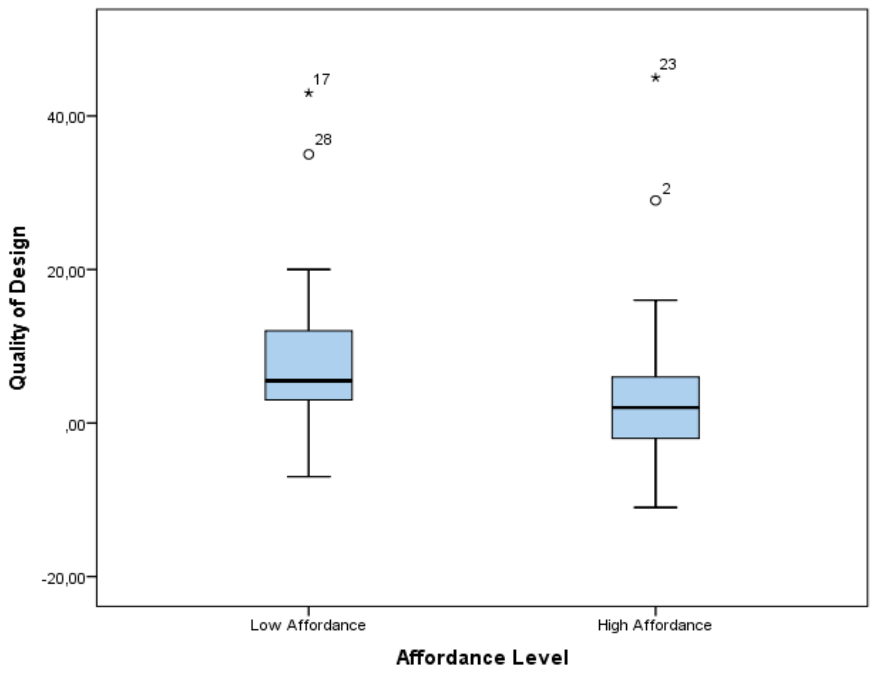

Figure 20 - Boxplot of the distribution of participants' quality of design.

two from each condition – all outperforming the rest by a relatively large margin. Like previously, we cannot evict these values, as we have no evidence to state that these values are not genuinely unusual values. Hence, we accept the outliers in our data.

Further examining the assumption of normality for both distributions, we discover that neither the low affordance nor the high affordance condition is normally distributed. In Appendix C, we argue for still doing the test, although we are violating the assumption of normality, as both groups are similar in both size and skewedness.

Testing for quality of design was similar to testing for design fixation, as shown in Table 8. This independent samples T-test used affordance as independent variable, and the quality of design metric as dependent variable. As with design fixation, we see that there is no statistically significant difference between the mean values of the two conditions, *t(31) = 0.894, p =.378*. Based on this result, we conclude that there is no statistical evidence to say that one condition is performing differently than the other regarding quality of design.

Table 8 - Independent samples t-test on quality of design. The non-significant result is highlighted in grey.

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Quality of Design	Equal variances assumed	,038	,848	,894	31	,378	4,31955	4,83271	-5,53684	14,17593
	Equal variances not assumed			,896	30,997	,377	4,31955	4,82172	-5,51447	14,15356

4.2 Demographics and Other Observations

In order to fully understand our data-set, we tried several approaches for analyzing our data. This included running the data through several third-party applications, including Microsoft Excel™, a Python script running an Apriori datamining algorithm (see Agrawal & Srikant (1994) and Han, Pei & Kamber (2011)), and MatLab™ pre- and post-processing scripts, all included in the appendices.

We consider the application of the Apriori algorithm an ineffectual, yet assuring, attempt, as this type of algorithm is advised for cases with amounts of data which makes conventional statistical analysis impractical. However, the pattern findings confirm the results from the independent samples t-tests. As can be seen in Appendix G, the two most common two-attribute patterns to occur together are 'Male; Holding Force Weighting 3' and 'Male; Complexity Weighting -2'. The latter of these patterns implies an unexpected finding of the experiment data analysis, namely the relationship between gender and weighting of complexity, while the former turns out to be insignificant, as there is no great variance between the genders.

As we recorded several other parameters and variables than those described in the previous sections of this chapter, we wanted to share some of these insights here. Upon completing the iterative design round, each subject completed a questionnaire asking for select background and demographic data. This data included achieved level of education (including specialization, field and graduation year), planned education, professional work experience (specifying both field and amount), age and gender.

Taking a closer look at the student population, we have found some interesting results from differences in the aforementioned demographic data. Sorting the student population by gender, we have 11 female participants and 13 male participants. Of these 11 females, 6 were subject to the 'low affordance' condition, and 5 were subject to the 'high affordance condition. Of the 13 males, 6 were subject to the 'low affordance' condition, and 7 were subject to the 'high affordance condition. Consequently, we will now show some independent samples t-tests, where the student sub-population is sorted by gender.

4.2.1.1 Independent Samples T-tests on Weightings of Attributes, Sorted by Gender

When sorting concept weighting on gender (and not affordance), we get the distribution displayed in Figure 21. Note the large difference in weighting of complexity for males (M = -1.38, SD = .961) and females (M = 0, SD = 1.375). We observe several outliers, and accept these as genuinely unusual values, as explained in Appendix D. Additionally, when testing for normality, only ‘weighting of disengaging force’ is normally distributed. However, as the group sizes are quite similar, we continue performing the t-tests.

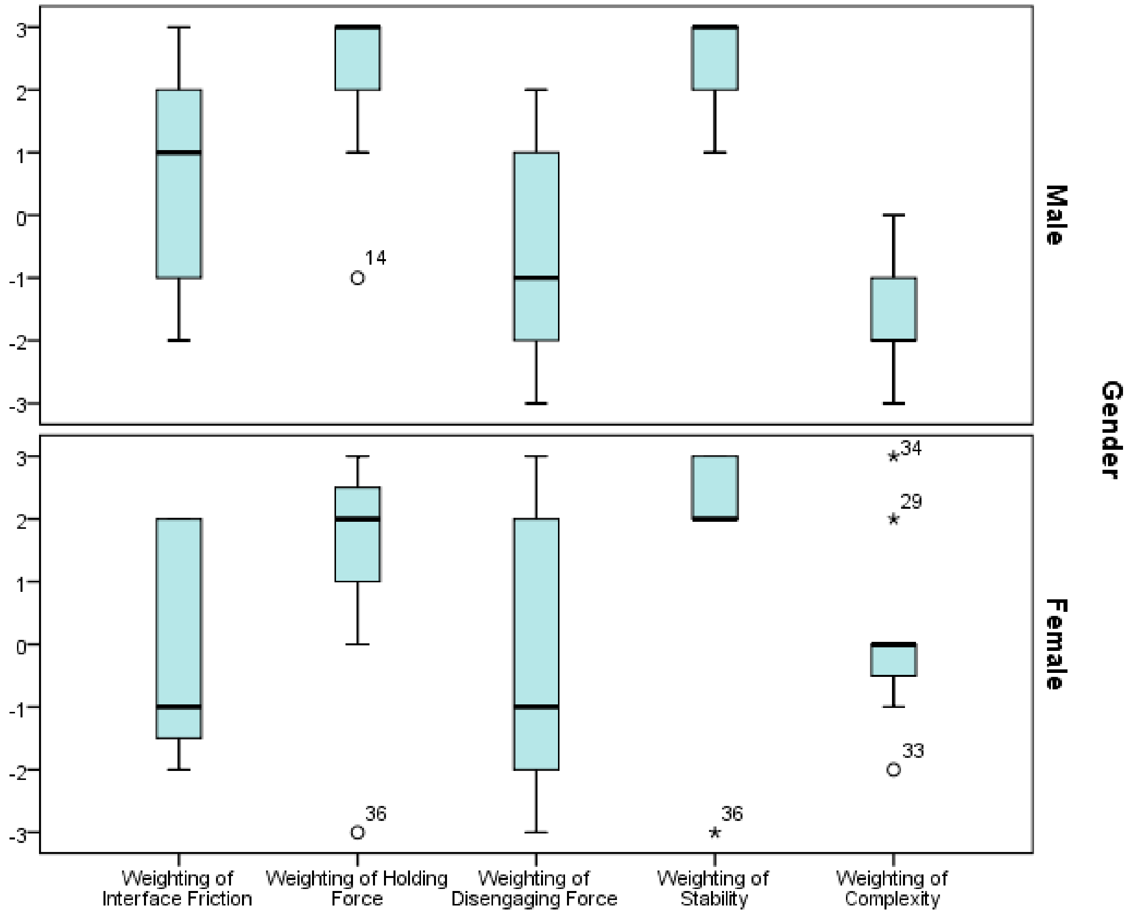

Figure 21 – Box plot of student participants’ weighting of concepts, sorted by gender. Mild outliers are marked by circles, and extreme outliers are marked with a star, both with unique participant IDs.

Testing with gender as the independent variable and the attribute weightings as dependent variables, we get the results displayed in Table 9. Here, the men rate ‘complexity’ as influencing the concepts in a more negative manner than women, more precisely by -1.476, 95% CI [-2.467 to -0.484], which is a highly significant difference, $t(22) = -3.085$, $p = .005$.

Table 9 - Independent samples t-test on weightings of attributes, using the student population, sorted by gender. Significant results are highlighted in yellow, and non-significant results are highlighted in grey.

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Weighting of Interface Friction	Equal variances assumed	,151	,702	,900	22	,378	,629	,700	-,821	2,080
	Equal variances not assumed			,895	20,900	,381	,629	,703	-,833	2,091
Weighting of Holding Force	Equal variances assumed	1,675	,209	1,269	22	,218	,776	,612	-,492	2,045
	Equal variances not assumed			1,224	16,558	,238	,776	,634	-,564	2,117
Weighting of Disengaging Force	Equal variances assumed	1,232	,279	-,753	22	,460	-,601	,799	-2,258	1,056
	Equal variances not assumed			-,742	19,774	,467	-,601	,810	-2,293	1,090
Weighting of Stability	Equal variances assumed	,357	,556	,723	22	,477	,385	,532	-,718	1,488
	Equal variances not assumed			,682	13,297	,507	,385	,564	-,831	1,600
Weighting of Complexity	Equal variances assumed	,036	,851	-3,085	22	,005	-1,476	,478	-2,467	-,484
	Equal variances not assumed			-2,994	17,482	,008	-1,476	,493	-2,513	-,438

4.2.1.2 Independent Samples T-tests on Quality of Design, Sorted by Gender

Furthermore, when looking at the ‘quality of design’ parameter sorted by gender, we get the distribution displayed in Figure 22. Here, large differences were seen between males (M = 12.85, SD = 17.155) and females (M = 1.36, SD = 6.918) regarding the ‘quality of design’ metric. Consequently, we wanted to run the tests for ‘quality of design’ for this sub-population, using gender (instead of affordance) as the independent variable for the

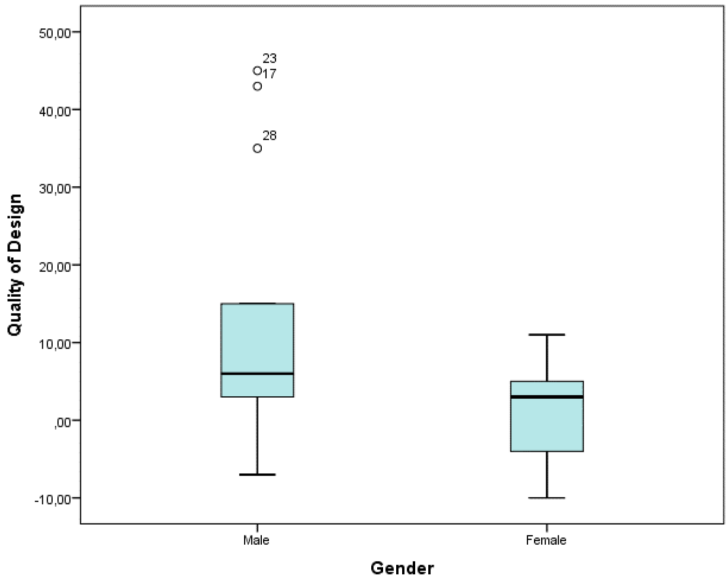

Figure 22 – Box plot of student participants' quality of design, sorted by gender. Mild outliers are marked by circles, and have unique participant IDs.

test. Hence, we are testing the independent samples T-test with gender as the independent variable, and quality of design as the dependent variable. In the distribution of Figure 22, we observe three outliers. These are accepted as outliers in accordance with the reasoning of Appendix D. Furthermore, when checking for normality, we see that the male distribution is slightly skewed (in the positive direction, as shown in Appendix C). As the male and female group size is roughly similar, and the t-test is fairly robust, we continue the t-test.

Results from the independent samples t-test are displayed in Table 10. Here, we see that the males' performance is 11.483, 95% CI [0.487 to 22.478] higher than that of the females, with the difference being significant, $t(16.331) = 2.210, p = .042$. It is also worth noticing the great standard deviation of the male participants, being almost three times the size of the female participants' standard deviation.

Table 10 - Independent samples t-test on quality of design, using the student population, sorted by gender. The significant result is highlighted in yellow.

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Quality of Design	Equal variances assumed	5,898	,024	2,076	22	,050	11,48252	5,53110	,01172	22,95331
	Equal variances not assumed			2,210	16,331	,042	11,48252	5,19514	,48745	22,47759

4.3 Evaluation of Hypotheses

As the goal of running this experiment has been to evaluate the hypotheses presented in section 3.1, we will attempt to do so here. This evaluation will be based on the statistical evidence provided in the previous sections.

4.3.1 Problem and Concept Understanding Hypothesis

Having chosen to evaluate this hypothesis by using two statistical tests, we examine the two sets of results individually before evaluating the hypothesis as a whole. The statistical test on problem understanding shows that there is no statistical evidence that interactions with prototypes of different levels of affordance will lead to different weightings of the pre-defined attributes. Furthermore, the statistical test on concept understanding shows that there is some statistical evidence that interactions with prototypes of different levels of affordance will lead to different evaluations of the pre-made concepts. In the latter test, we find three statistically significant ($p < .05$) differences between the two conditions – these being 'Concept A Holding Force Rank' ($t(31) = 2.099, p = .044$), 'Concept B Disengaging Force Rank' ($t(31) = -3.158, p = .004$) and 'Concept D Friction Rank' ($t(28.608) = 2.678, p = .012$). To summarize; the statistical evidence supports the null hypothesis regarding problem understanding, but (contrastingly) supports the alternative hypothesis regarding concept understanding.

4.3.2 Design Fixation Hypothesis

For the evaluation of the design fixation hypothesis, we review the results from section 4.1.2.1. This independent samples t-test shows no statistical evidence that the groups' means are different ($t(31) = -0.240, p = .812$). Although we find the means to somewhat differ between low affordance (M = 2.94, SD = 1.807) and high affordance (M = 3.07, SD = 1.304), this does not give proper foundation for concluding that there is a difference. Hence, the statistical evidence presented here supports the null hypothesis, stating that the level of affordance does not (in this experiment) impact design fixation.

4.3.3 Learning Activity Hypothesis

Lastly, the evaluation of the learning activity hypothesis is based on the results from section 4.1.2.2. As presented there, this independent samples t-test shows that we do see an indication that the means of participants using low affordance prototypes (M = 9.60, SD = 13.344) being slightly different from the means of those using high affordance prototypes

(M = 5.28, SD = 14.354). However, there is not enough statistical evidence to state that participants using low affordance prototypes will produce designs with different quality than participants using high affordance prototypes ($t(31) = 0.894$, $p = .378$). Hence, the statistical evidence supports the null hypothesis.

4.4 Interpretation of Experiment Results

The results previously presented in this chapter have been descriptive, attempting not to draw early conclusions nor hasted implications. In this section, we will address some interpretation of the presented results, before continuing with limitations of the experiment (in chapter 5) and implications of the results (in chapter 6). Some of these interpretations are indeed subjective, where we try to give some insights as to how we interpret our results.

4.4.1 Problem and concept understanding hypothesis interpretation

In the hypothesis for concept understanding, the results state that there *might* be some difference as to how the affordance level may affect concept evaluation. If we compare the mean values of the rankings that are statistically significant from the concept understanding hypothesis (i.e. ‘Concept A Holding Force Rank’, ‘Concept B Disengaging Force Rank’ and ‘Concept D Friction Rank’) to the expert evaluation scores in Table 1, we see that the low affordance condition is closer to the expert evaluation in all three rankings. This can be interpreted as the low affordance condition performing better than the high affordance condition in this specific setting. There are several limitations and implications to these results, especially regarding the expert evaluation of concepts, which we address in the limitations chapter (Chapter 5).

Further, we assumed the problem and concept understanding scores would make the same implications. The statistical analysis of the data shows that this was not the case, as there are no results showing any tendency towards either group weighting the attributes’ importance differently. A possible explanation is that the problem was represented in the same way for both groups, by textual description. It seems this test was insufficient, and the different representation of the concepts influenced the problem understanding to a very small degree.

4.4.2 Design fixation hypothesis interpretation

Moving on to the design fixation hypothesis, there is little room for interpretation as to what the statistical evidence is stating; that the level of affordance does not have a statistically significant impact on design fixation. However, we can qualitatively say – from doing the expert evaluation – that all participants’ designs contain large variations regarding both fixation and quality (as we see in the large standard deviations).

4.4.3 Learning activity hypothesis interpretation

The quality of design metric from the evaluation of the learning activity hypothesis show no significant difference between the two differently conditioned groups. There is a slight tendency for the participants initially conditioned with low affordance prototypes to perform better when studying the mean values. Unlike the participants initially conditioned with high affordance prototypes, the low affordance group have been interacting with the same tools in both the evaluation round and the iterative design round. Still, there is no statistical significant evidence of different performance between the two groups. The advantages of already being familiar with the affordance level tools and the possible gain of information from the high affordance prototypes might be able to outweigh one another, but this study is not sufficient to conclude either way.

4.4.4 Interpretations of other observations

Lastly, we find it very interesting that when studying sub-populations within our data, we encounter varying statistical results (that can be found in Appendix C). For example, the differences in male and female weighting of complexity is apparent in Table 9. We do not want to interpret these results to make hasted conclusions, but rather use these insights to fuel questions for discussing both limitations and implications of our research.

A surprising finding of this study is the difference in performance between the genders. While the affordance conditioning had no great infliction on the weighting of the physical attributes in the evaluation round, the analysis shows a statistically significant difference in the weighting of complexity between the genders. The evaluation of the male sub-population is closer to the expert opinion. Additionally, the quality of designs of males perform better than those of females. That is not to say women perform the tasks worse than men. It is important to note that the expert evaluation is performed by males, although without considering participant gender. The initial problem from Kongsberg Automotive, the formulation of the task, the advisory of the experimentation, and the objective evaluation of the results is exclusively done by males. One possible explanation of the quality of design results is that the male dominated environment where the task is extracted from, task description, and evaluation might be creating an environment in which women are not facilitated to thrive as much as men.

5 Limitations

In this study, there are several limiting factors that needs to be considered. This chapter attempts to highlight some of the most impacting factors that we think have affected our results, and that could preferably be changed for future endeavors of similar nature.

The subjects that have participated in this study have been selected from two sub-populations, both being fairly homogenous on their own. However, we see a spread in several factors, including nationality, previous work-experience, education and age. Moreover, we have shown that there are significant differences between the genders' performance in this experiment, and would like to point out that all female participants in this experiment were from the student sub-population. Hence, we would also like to include a larger number of participants from the Kongsberg Automotive sub-population, preferably with a gender-distribution that is representative for this company.

The pre-made concepts that are presented in this thesis are provided by Kongsberg Automotive's research and development department. Hence, there are several things to consider regarding biases that this may introduce, and we believe the presentation pre-made concepts to have a substantial impact on the experiment results. Firstly, the engineers who participate from Kongsberg Automotive are familiar with both problem space and similar technology that is introduced during the experiment. We have tried to mitigate this effect by creating abstractions of the problems, but we cannot rule out that making these abstractions have removed or added dimensions and/or complexity to the experiment. Secondly, although each high affordance prototype was checked for loose screws and other signs of wear in-between experiment runs (and replaced with spare parts if necessary), we cannot rule out the prototype interactions of one participant impacting the next participant. Additionally, we had to opt for using some 3D-printed parts on the high affordance prototypes due to lack of (V-slot) bearings. We attempted to mitigate this effect by including the same amount of 3D-printed parts in all concepts (Figure 23), resulting in the wagons having somewhat increased friction when moved along their respective rails. Also note that this friction is *not the same* as 'interface friction', but may ultimately impact the participants' perception of the concepts, thus impacting the results.

Figure 23 - 3D-printed bearings introduce more friction to rail mechanisms in all concepts.

While the problem and concept understanding hypothesis is based on participant deliverables, the design fixation hypothesis and learning activity hypothesis is based on an expert evaluation of participant deliverables. We initially tried using two independent evaluators (both being professors of mechanical engineering at NTNU) for setting a baseline for the pre-made concepts (providing both high and low affordance prototypes). After not being able to get the two evaluators to agree on equal terms – and due to time constraints and availability – we decided to use their input for creating our own expert evaluation. Consequently, this evaluation has a large impact on both the design fixation hypothesis and the learning activity hypothesis.

Continuing on the topic of design fixation; we believe there to be an effect caused by the ‘fidelity’ of the prototypes presented in the experiment. This is another form of ‘fixation’, where the user perception of the prototypes may be altered due to material, color, surface finish and other properties. This also includes the low affordance prototypes in that the drawings include select templates, line thicknesses and labels. Although we can argue that the CAD-models of the pre-made concepts are *almost identical* to the physical (high affordance) models, we cannot state that they are *precisely identical*.

It is worth noting that while we have attempted to manipulate the level of affordance for this experiment, we cannot rule out the effect of product semantics – meanings that the product or model may have to the individual participants. In Research Paper II, we elaborate somewhat on the difference between affordance and semantics. Here, affordance is measured *before* interaction with the participant, whereas semantics are measured *after* interactions – thus incorporating some kind of interpretation and (product) meaning.

Lastly, we want to point out that while the deliverables from the evaluation round were unambiguous and without much room for interpretation, the deliverables from the iterative design round could possibly have been more defined (and pilot tested) before being incorporated into the experiment – as these deliverables were highly dependent on the said expert evaluation.

The limitations of the study are not confined to the contents of this chapter, but we have attempted to cover the most important limitations. Ultimately, we want to increase the repeatability of both experiment setup and results, making it easier to contribute to the growing research community doing experiments on engineering design.

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6 Implications

As discussed in the previous chapter, there are many limitations. These taken into account, this chapter will discuss the implications of the performed study, and how we speculate that the results will (and should) impact future efforts on similar topics.

With the hypothesis for problem and concept understanding in mind, we found (to our surprise) that the participants conditioned with low affordance prototypes perform slightly better than those conditioned with high affordance prototypes. With the theory discussed in Chapter 2 in mind, one would expect the high affordance prototypes to provide more information, and thus, a better basis for making a good evaluation. However, there seems to be a disconnect between theory and real-world application of the affordance-term, especially for physical models that are in-development. It could be argued that the 20 minutes given to read instructions, comprehend the problem and evaluate the concepts was insufficient to grasp the amount of information provided by the high affordance prototypes, and that this effect is what we are measuring in our experiment. Hence, implicating that while high affordance prototypes embody more perceivable knowledge, they require more time and interaction to understand. Also, the amount of information present in the high affordance prototypes might cause fixation on the physical attributes (e.g. surface finish, materials, rigidity of construction etc.).

Furthermore, the sunk cost effect, as discussed by Viswanathan & Linsey (2013), is assumed to be present in ideation activities, as design fixation occurs when designers become sufficiently invested in their designs. The inconclusive findings of our study regarding the design fixation hypothesis supports the argumentation made in Research Paper II, stating that the sunk cost effect is less present in scenarios lacking time investment. Hence, the lacking time investment in this experiment makes a case similar to the studies by Kiriyama & Yamamoto (1998) and Youmans (2011), where controlled studies were performed, the time limited, and the sunk cost effect was not observed. We regard our results to be in line with these two studies, showing an absence of the sunk cost effect in scenarios lacking investment of effort and time (Viswanathan & Linsey, 2013).

The initial idea of this experiment (besides testing the impact of prototype affordance) was to test the Kongsberg Automotive employee sub-population in comparison to the student sub-population. However, upon failing to gather the required number of participants for running such a statistical comparison, we decided to leave this out of the thesis. However, we have included some preliminary statistics in Appendix C, showing that we still believe this to be a highly interesting comparison, as most studies made on the performance of designers are executed with students as the only participants. Testing the current theory on design fixation and learning activities, among others, is important to compare the practices in the industry with those of students beyond qualitative studies. Although we were ultimately unsuccessful in gathering a sufficient sub-population of professional engineers, we regard this type of experiments to contain great potential.

Ultimately, we believe we have found an untapped potential in studying affordance in prototypes, both in theory, current and best practice. Additionally, we believe there to be an important, albeit difficult, task to distinguish between prototype affordance (information and physicality) and prototypes semantics (information and meaning). We believe that the framework for using affordance to impact prototyping in product development needs several improvements, as the application and manipulation of affordance has proven more difficult than initially estimated.

7 Conclusions

In Part I of this Master's Thesis, we have attempted to make several contributions to the current literature on engineering design and product development. Firstly, we have attempted to provide a holistic and thorough walkthrough on relevant literature in engineering design, including topics of knowledge transfer, learning cycles, prototyping, design fixation and requirements elicitation. These topics have been presented in detail, supporting the content of the appended Research Paper I, II and III. Additionally, the framework for using the Audience-Intent Model for categorizing early stage prototyping efforts has been presented, highlighting internal, reflective prototypes as an untapped tool for leveraging tacit knowledge within teams.

Secondly, the layout for a design experiment testing the evaluation of pre-defined concepts have been presented, testing prototype affordance in design activities, Additionally, experiment results are presented, studying a population of 33 participants of both engineering graduate students and professional practitioners as subjects. Here, we have presented and evaluated three hypotheses, the problem and concept understanding hypothesis, the design fixation hypothesis and the learning activity hypothesis. The results from this experiment indicate that while we see little evidence that changing prototype affordance impacts problem understanding, there are indications that prototype affordance does affect concept evaluation. There is little statistical evidence indicating that the affordance impacts design fixation or quality of design. However, limitations as to the measurement of both these metrics are discussed, and the more research on the impact of affordance on these topics are accentuated.

Ultimately, we believe there to be an untapped potential in researching prototype affordance for transfer of knowledge in product development, and encourage future research to address this potential further.

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Part II: Appended Research Papers

While working on our thesis, we have managed to publish three conference articles for three scientific conferences. The first article is already published in the conference proceedings, and the two latter articles are approved and in press for publishing during the time of writing. These literary contributions include:

Using Prototypes to Leverage Knowledge in Product Development: Examples from the Automotive Industry

This article by Erichsen, Pedersen, Steinert & Welo (2016) was published in the "2016 IEEE International Systems Conference (SysCon 2016) Proceedings". The conference was held on April 19th through 21st in Orlando, Florida, and the conference presentation was done by Jørgen A. B. Erichsen.

Learning in Product Development: Proposed Industry Experiment Using Reflective Prototyping

To be held on 15th through 17th of June 2016, "The 26th CIRP Design Conference" takes place in Stockholm, Sweden.

Prototyping to Leverage Learning in Product Manufacturing Environments

"The 6th Conference on Learning Factories", to be held on 29th through 30th of June 2016, takes place in both Gjøvik and Raufoss.

Research Paper I

Using Prototypes to Leverage Knowledge in Product Development: Examples from the Automotive Industry

Erichsen, Jorgen A. B., Andreas Lyder Pedersen, Martin Steinert, and Torgeir Welo. Using Prototypes to Leverage Knowledge in Product Development: Examples from the Automotive Industry. I: 2016 IEEE International Systems Conference (SysCon 2016) Proceedings. Orlando, Florida: IEEE 2016 ISBN 978-1-4673-9518-2. s. 491-496

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Using Prototypes to Leverage Knowledge in Product Development: Examples from the Automotive Industry

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***Abstract*—This article is rooted in the automotive industry as starting point, and discusses the topic of leveraging tacit knowledge through prototypes. The aim of this study is to make the case of using reflective and affirmative prototypes for knowledge creating and transferal in the product development process. After providing an overview on learning and knowledge, the Socialization, Externalization, Combination and Internalization (SECI) model is discussed in detail, with a clear distinction between tacit and explicit knowledge. Based on this model, we propose a framework of using said reflective and affirmative prototypes in an external vs. internal learning/knowledge capturing and transferal setting. Rounded by two case examples from the automotive industry we end by identifying the emergent research questions and areas. Using prototypes and prototyping may hold a monumental potential to better capture and transfer knowledge in product development, thus leveraging existing integration events in engineering as a basis for knowledge transformation.**

Keywords—knowledge transfer; internal reflective prototypes; prototyping; tacit knowledge; integration events; product development; automotive engineering

I. Introduction and Background

In this paper, we argue for increased usage of reflective and affirmative prototypes for knowledge creating and transferal in the product development (PD) process. This paper attempts to make two literature contributions. The first is to provide a mapping of relevant literature on knowledge in PD. This section includes an overview of select topics, including organizational and individual knowledge, in addition to some current practices on knowledge transfer. A brief introduction to learning mechanisms is given, with integration events and knowledge owners as key aspects for lean product development in systems engineering. Furthermore, a synthesis on the Socialization, Externalization, Combination and Internalization (SECI) model [1] is presented, with its relation to tacit and explicit knowledge.

The second contribution is to provide a short overview of prototypes and prototyping, and their relation to knowledge transformation processes in PD. This paper proposes a model of four prototyping categories, with each aspect of the model briefly explained with examples. Examples on contextual internal, reflective prototypes from real-world settings are provided, and their relation to knowledge acquisition and transfer is emphasized. Lastly, the possibilities within said research space are presented, with a coarse mapping of interesting topics that need further investigation.

The automotive industry is subject to an immense pressure to develop new products ever faster due to steadily increasing competitive pressure. Being an industry in constant evolution, with increasing focus on both reducing lead times and emphasis on quality, a lot of research is targeting aspects of knowledge and the mechanisms of increased learning in new PD. For example, knowledge-based development has been established as a viable method [2] for extracting the base points of Toyota's PD process [3]. In this paper, we will focus onto knowledge, its creation and its transfer in a PD organization.

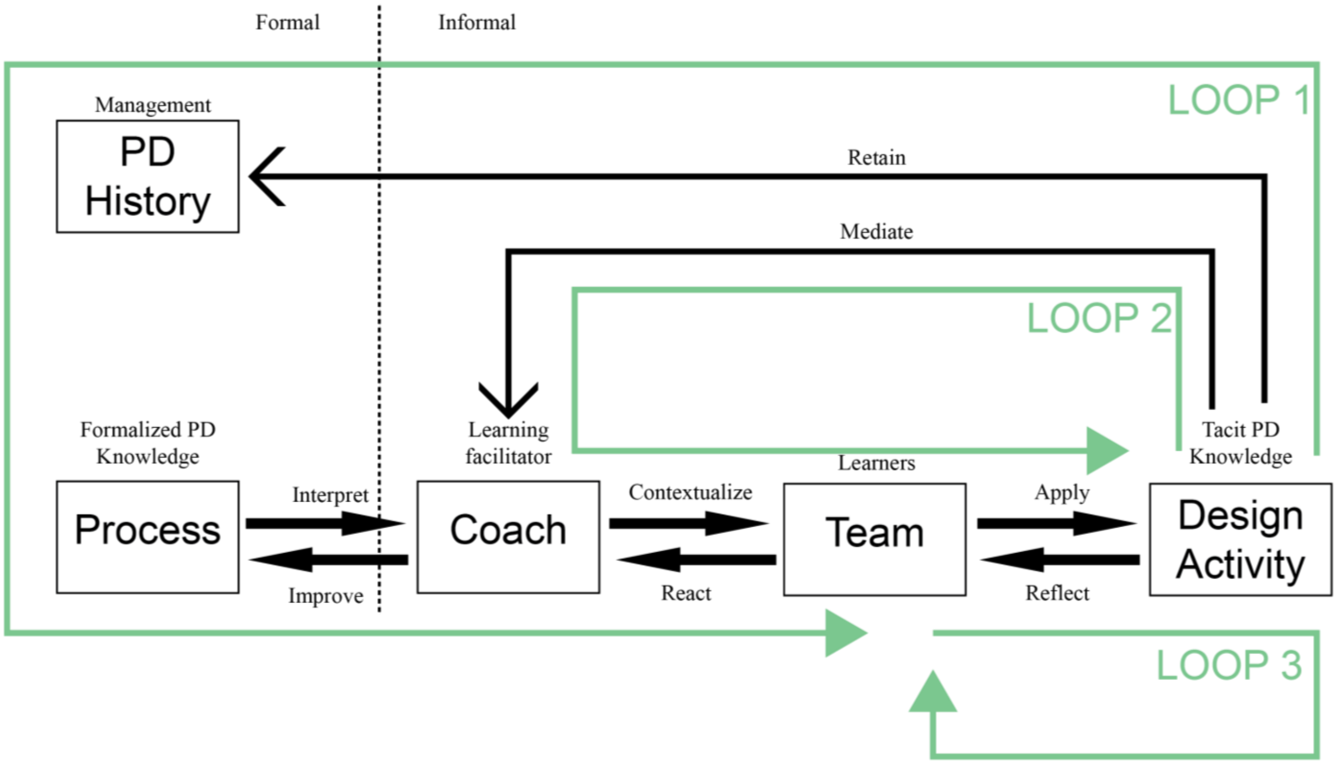

Fig. 1 - Learning Mechanisms in Product Development, adopted from [11].

In the automotive industry, making mistakes may cost you dearly. With (relatively) low cycle times, the costs of making mistakes in the later stages of PD are immense, having major implications further down the value stream. Also, automakers cannot develop knowledge from scratch every time they start new projects. Thus they aim to keep a large base of standardization of parts and processes within a product-technology platform to ease the burden on the PD team(s). Hence, managing and controlling the knowledge within the company becomes an important issue.

For our research, we have access to several industrial liaisons, including a multinational automotive tier 1/2 supplier company. Many of our insights and proposed discussion points are gathered from case-examples, semi-structured interviews and conversations with said liaisons [4].

II. Theory: Knowledge in Product Development

There are numerous definitions of knowledge provided in the literature [5]. Wisdom and knowledge are differentiated by [6], defining wisdom as evaluated understanding (“know-why”) and knowledge as application of data and information (“know-how”). Reference [7] argues that knowledge can be divided into individual and organizational knowledge. Organizational knowledge is defined as the sum of what is learned, perceived, experienced or discovered (by individuals) during a project (in the organization). Individual knowledge has three main categories; experience-based, information-based and personal knowledge [8]. Interactions of individuals are the main ingredient of organizational knowledge, and that this knowledge exists between (and not within) individuals [9].

A. *Defining Integration Events and Knowledge Owners*

Most companies use a stage gate process in PD. However, stage gate is an investment-based governance process. Hence there is a call for more event-driven approaches for improved organizational learning as this aspect becomes increasingly important in competitive consumer businesses. One of the more recent practices is the use of so-called ‘integration events’ [10]. These events are reported to ensure better insights and information while preserving other know-hows, providing a basis for transforming project knowledge into organizational learning. Integration events are ‘learning cycle gates’ where informal knowledge is formalized (made explicit), and formal knowledge is interpreted. When these events are systematically applied, they become learning loops [11]. Hence, the key to organizational learning is in the mutual exchange of knowledge between the individuals and the organization.

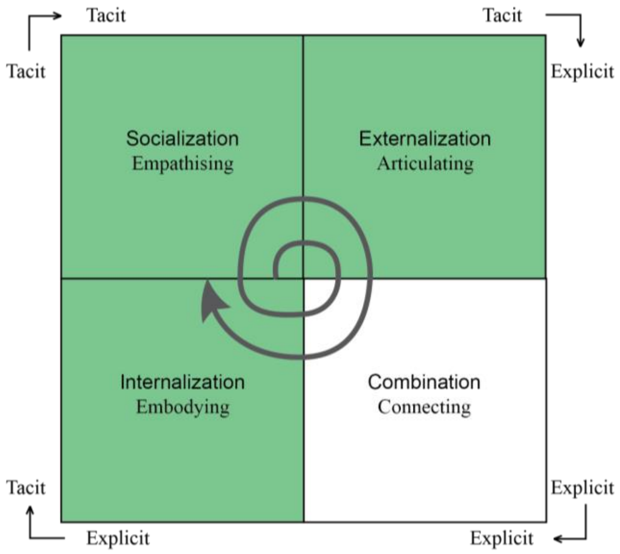

Fig. 2 The SECI model, with highlighted areas of interest [1].

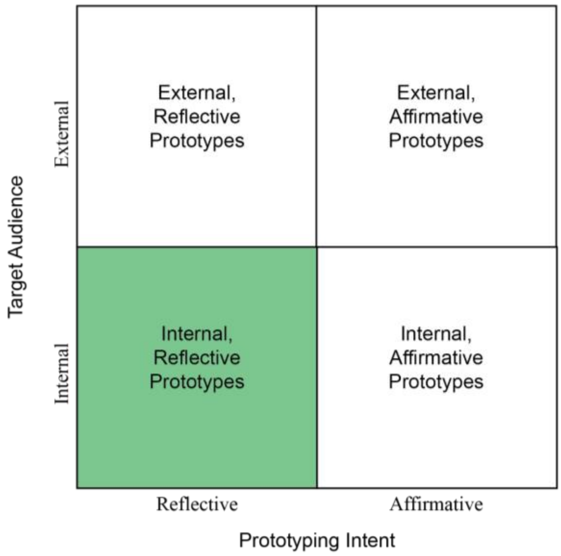

Fig. 3 A proposed model of four prototyping categories.

As a catalyst for this exchange of knowledge, many companies deploy key experts or learning facilitators. These are engineers and so-called 'knowledge owners' within each project, providing organizational grounding, previous insights and know-how for the PD team. For example, Toyota is well-known for using functional managers to employ existing knowledge within projects, and chief engineers to challenge the existing standard by being the customer representative [3]. As a result of being part of the development team, these knowledge owners gain insights and experience – thus contributing to organizational learning as long as they are part of the ongoing projects. In (Fig. 1), adapted from [11] and [12], three different types of learning loops within the PD knowledge acquisition processes are illustrated.

B. Tacit and Explicit Knowledge in PD

Closely linked to organizational knowledge, is the differentiation between tacit and explicit knowledge. Explicit (i.e. formal) knowledge, learning loop one, includes information-based, fact-based [13] learnings that are summarized in knowledge artifacts [14]. An example of knowledge artifacts within the automotive industry is the use of A3s, described by [3] and [15]. Tacit (i.e. informal) knowledge, learning loops two and three, is the know-how, the craft, the skill and learnings of the product engineering individuals [16]. Tacit knowledge is hard to formalize and to make explicit, as this kind of knowledge is stored within interactions, experiences, instances and discoveries. We argue that one key dimension of tacit knowledge is the interactions with (and use of) objects and experiences in the product engineering processes, often referred to as prototypes in one form or another.

C. The SECI-model and Transfer of Knowledge in PD

In [1], the prevalent model for dynamic knowledge creation has been proposed. Here, the SECI process (Fig. 2) is presented, explaining the enhancement of knowledge creation through conversion of tacit and explicit knowledge. The SECI process spirals through four stages, including socialization, externalization, combination and internalization. The model further proposes certain knowledge assets as facilitators of knowledge creation. Knowledge assets are categorized as experiential, conceptual, systemic and routine. This model has gained major traction, and a study by [17] concludes conceptual knowledge assets (i.e. early stage PD insights) to have the most effect on knowledge creation.

The socialization (tacit-to-tacit), internalization (explicit-to-tacit) and externalization (tacit-to-explicit) stages of the SECI process describe the setting of tacit knowledge creation and transfer in development teams and organizations. Socialization in the context of transferring tacit knowledge includes creating a work environment which encourages understanding of skills and expertise through practice and demonstrations, while internalization includes conducting experiments, sharing results, and facilitating prototyping as a means of knowledge acquisition [1]. The study conducted in [17] concludes conceptual knowledge assets to be the most efficient tool in facilitating internalization and externalization. Conceptual knowledge assets are defined as "knowledge articulated through images, symbols and language" [1] – and although not explicitly identified in the definition – it can be argued that prototyping is encompassed by the term conceptual knowledge assets.

D. A Proposed Model of Prototyping Categories

In general, prototypes are defined as "An approximation of the product along one or more dimensions of interest" [18], thus including both physical and non-physical models, e.g. sketches, mathematical models simulations, test components, and fully functional preproduction versions of the concept [19]. Further, prototyping is defined as the process of developing such an approximation of the product [18].

Taking a broad perspective, we propose that prototypes and prototyping may be divided in a two-by-two metric (Fig. 3). On the first axis, the intent (of the prototype) can be split into two sub-categories; “reflective” and “affirmative”. On the second axis, inspired by [20], the target audience is split into “internal” and “external”. By using this two-by-two metric, we map four different prototyping categories. These four are:

Fig. 4 An early wooden prototype of the ‘X1 Experimental Vehicle’.

1) External, affirmative prototypes: These prototypes display an approximation of a nearly finished pre-production model, and are typically the prototypes presented for validation or showcasing purposes, or namely alpha/beta prototypes [21]. Both appearance and relative functionality is high, and these prototypes are often used for marketing or external validation (e.g. New Car Assessment Programme (NCAP) tests) etc.

2) Internal, affirmative prototypes: These prototypes are focused in terms of function, and can be subject to function, reliability and manufacturability testing. Examples of these prototypes are the combination of subsystems, fatigue testing of a conceptual prototype or a project milestone to validate the progression of the team. These prototypes are rarely shown to external audiences.

3) External, reflective prototypes: These prototypes are often concepts displayed to external sources for feedback in early stage development. The response and reaction gathered from observing a user interacting with a prototype expressing the basic functionality of a concept can provide useful insights and be a time-saver.

4) Internal, reflective prototypes: These are the prototypes the PD team uses to learn internally and conceptualize their ideas. Internal reflective prototypes are learning tools. Their purpose is conceptualizing ideas, and might focus on certain functionalities or suggest appearance of a product concept [22]. Internal, reflective prototypes are used for learning, enabling experiences and insights through interactions. Generally, these prototypes are low fidelity [20], and often thrown out after the projects are finished.

The insights, experiences, interactions and learnings, created by means of the internal, reflective prototypes lay the foundation for the tacit knowledge accumulated within the PD team. How this knowledge is captured, stored and utilized, however, is not well described in the literature.

Fig. 5 Finished ‘X1 Experimental Vehicle’ at Stanford University.

In [23], Simon identifies a gap between professional knowledge and real world practice. The foundation of a “science of design” is drawn up, applying methods of optimization from statistical decision theory. He thus lays the basis for a scientific approach of treating knowledge.

This is criticized in [24] by Schön for its presumption of technical rationality. He argues instead that the real challenge lies not in the treatment of well-formed/modeled requirements, but in the extraction of these, often unknown, requirements from real-world situations. The practical unknown unknowns are the core challenge. In [25], he thus proposes reflective iteration rounds as the learning tool with the biggest potential. Schön also points out that creation/translation of explicit knowledge, is a major difficulty. Together, Simon and Schön thus represent the knowledge creation spiral in the SECI model.

III. Examples: Knowledge Transfered from Prototypes

In the following sections, we attempt to exemplify the internal, reflective prototypes by providing findings from two case studies. Both cases come from an automotive concept setting at Stanford University, with the prior being the development of a multi-modular vehicular research platform, and the latter being a dynamic hunter-gatherer approach [26] to the future autonomous driving experience.

A. *Case I: Real Industry Case with Reference*

Collaborative efforts between the Dynamic Design Laboratory [27] and Product Realization Laboratory [28] at Stanford University to create a steer-by-wire prototype. This project, later dubbed as the ‘P1’, was an electric vehicle with independent rear-wheel drive, and also independent left and right steering mechanisms. This car was first done as a one-off to test steering mechanism redundancy, independent torque control, maximize handling performance and minimize tire wear, but the project was later extended in another project, dubbed the ‘X1’.

As the P1 was first built as a research vehicle, the team had several insights as to how to improve this setup for further

Fig. 6 Early prototype on increasing autonomous car passenger comfort.

testing when building the X1. Hence, the X1 was built to be modular, rather than fixed, with different testing modules and systems fitting together on a single test platform. During the early stages of the X1 project (Fig. 5), the team discovered that simple design decisions on single aspects of the car altered a vast amount of other aspects, making the planning of everything (i.e. in SECI-terms: both externalization and internalization) before building a prototype a very difficult task. Indeed, a CAD process failed utterly. As a result, the team planned the car structure (with modules, their relations and critical functions) in physical mock-up prototypes, using wood (Fig. 5) for convenience and learning speed. This way, they could iterate rapid designs, reflect, and gain new insights on the systems and their relations to each other in a short amount of time.

B. *Case II: ME310 Product Innovation Renault Prototype*

During the mechanical engineering course of ME310 [11] at Stanford University, a team working with Renault had the challenge of redefining the future autonomous driving experience, especially regarding passenger trust towards the vehicle. In (Fig. 6), we see an explorative prototype made by the team. The prototype is a plate, mounted in the passenger foot well to represent pre-queuing braking motion by small actuation in fully autonomous vehicles. The prototype was used as an initial road test within the development team, and lead to a new insight; that is, the interaction with the prototype facilitated increased passenger comfort. The insight is not captured within the prototype (the object), but rather within the interaction with the object. It is worth noting that the development team had a hard time understanding the cause of increased level of passenger comfort.

IV. Research Potential of using Prototypes in Knowledge capturing and transferring

There is certainly a need for further exploring the transfer of insight, learning and knowledge, especially through the use of physical tests and prototypes. The product developers and engineers of tomorrow will need a broad understanding of systems, enabling improved problem-defining (rather than problem-solving) skills, as the challenge in PD as a whole is to both define and solve problems. An experiment conducted in [29] focuses on the role of prototyping in the detection of design anomalies in a course of engineering students. When presented with initial examples containing certain bad features, some groups were made aware of the bad features, while others were not. The study concludes that certain bad features were excluded in the students own initial prototypes (i.e. before testing), while other bad features predominantly were not excluded until after the initial prototypes were tested. As stated in [29], there is a call for more research on understanding the students' preliminary selection of concepts, their understanding of systems, and the effect on both as a result of physical testing.

It is with respect to these insights that we define future research areas – and possibly fields. The research space of tacit knowledge transfer within PD is one promising focus. We would like to especially encourage exploring how prototypes (and prototyping) can be used as a catalyst for the tacit knowledge transfer. If the insights, experiences, learnings and interactions with prototypes accumulate tacit knowledge in the PD processes, how can one facilitate the PD process in such a way that most of the tacit knowledge is transferred – both internally (socialization), but also within the organization (externalization and internalization)? The ambiguous nature of tacit knowledge poses some challenges, especially regarding the capture of this knowledge, as this externalization is very difficult to automate.

After raising the question on how to accumulate (more) tacit knowledge, one can also argue that we need more understanding on how to capture the knowledge. How can the organization internalize the tacit knowledge, making it usable for others, and how can it be externalized back in the PD process when needed? We see a need to explore the importance of the human aspect of this tacit knowledge. How do human interactions influence the accumulation and transfer of tacit knowledge, and can we alter this for the benefit of the PD process? Can tacit knowledge be transferred by interactions with (other's) prototypes, or can you transfer the same insights through pictures? Are there instances, events or arenas that leverage the transfer of tacit knowledge, and how can we better design the PD processes for this purpose? Can we use objects (prototypes) as tacit knowledge artifacts, and can we use these to alter the learning or the PD team? If we find ways of accumulating, capturing and transferring tacit knowledge, how do we employ these methods and practices with minimum effort?

Ultimately, we are questioning whether there are there methods that can work for a) better internalization, and b) better externalization of tacit knowledge? How do we capture experiences, interactions and insights, and how do we store these? Can we use artifacts like pictures, video and text for capturing this knowledge? Are there prototypes that are better for capturing said knowledge, and if so, what are their properties? Are there any systematic tools that can be used for capturing and leveraging tacit knowledge? These are all questions that need attention in coming research.

V. Conclusion

The purpose of this article has been to propose a new research space, including prototypes and their use and impact on knowledge acquisition and transfer within PD organizations. This paper aims at taking a comprehensive view on the different kinds of knowledge provided in the literature, and bringing this into the context of engineering design. Individual knowledge and organizational knowledge have been differentiated, and some current knowledge capturing practices in the automotive industry have been briefly discussed.

A model on prototyping categories is proposed, mapped in a two-by-two metric in (Fig. 3). These categories are briefly presented, with the four categories being *external, affirmative* prototypes, *internal, affirmative* prototypes, *external, reflective* prototypes and *internal, reflective* prototypes. Two small case studies have been presented, with emphasis on prototypes and their effects on developing knowledge.

Lastly, this paper has attempted to map future opportunities within said research space. The need for a better understanding of how to deal with tacit knowledge – both within the PD team and the knowledge value stream of system engineering organizations – is evident. The use of prototypes in relation to tacit knowledge transfer is of particular interest. We expect their deployment to lead to more event-driven and thus leaner PD processes. This is a call for more research towards the use of prototypes and prototyping, especially covering the socialization aspects of knowledge transfer in engineering design.

Acknowledgment

This research is supported by the Research Council of Norway through its user-driven research (BIA) funding scheme, project number 236739/O30.

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Research Paper II

Learning in Product Development: Proposed Industry Experiment Using Reflective Prototyping

Erichsen, J. A. B., Pedersen, A. L., Steinert, M., & Welo, T. (2016). Learning in Product Development: Proposed Industry Experiment Using Reflective Prototyping. Procedia CIRP. http://doi.org/10.1016/j.procir.2016.04.142

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Learning in Product Development: Proposed Industry Experiment Using Reflective Prototyping

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Abstract

This article discusses the aspect of learning activities in product development by leveraging a strategy for capturing and transferring tacit knowledge through the extensive use of reflective prototyping. With the overall aim of finding new ways for organizations to learn faster, the theory from knowledge transfer is converted into a framework for using reflective and affirmative prototypes. Rooted in this framework, an automotive industry in-situ experimental setup for studying learning, continuous evaluation and knowledge generation in product development is proposed and discussed.

Selection and peer-review under responsibility of Professor Lihui Wang.

Keywords: internal, reflective prototypes; prototyping; learning activities; design fixation; product development; experiment

1. Introduction

In this article, we investigate learning in product development, and the influence of concept representations at varying levels of affordance. Specifically, this includes exploring the role of reflective prototyping and design fixation. This article attempts to make two contributions to current literature.

Firstly, we review the relevant literature relating to creation and transfer of knowledge in product development. Furthermore, we review the role of several types of prototyping, design fixation and the concept of affordance in the context of product development.

Secondly, we propose an experimental setup on the role of concept representations in (early phase) product development. This experiment is intended for a R&D department of a global automotive tier 1/2 supplier.

The automotive industry is subject to steadily increasing demand for faster development cycles and higher quality products. Making mistakes leads to costly and time consuming rework. The product life cycles are generally in the order of five to ten years. Thus, changes have major implications on manufacturing process and planning.

In the early phases of automotive product development projects, the problems and concrete solutions are yet undefined. The main focus is on mapping possible directions for the R&D team. In this phase, quick learning cycles and continuous evaluation and selection of concepts are key. Poorly based decisions will lead to rework. In this regard, learning from past projects and managing the company's tacit and explicit knowledge is of high importance. The proposed experiment attempts to uncover some tangible aspects of how to approach these issues.

2. Theory: Learning Activities in Early Stage Product Development

In (1, 2), Simon lays a foundation for a "science of design". This is drawn up due to the recognition of the gap between professional knowledge and real world practice, applying methods from optimization within statistical theory; thus, laying the groundwork for a scientific approach to treating knowledge in design work.

This is criticized by Schön (3) for assuming technical rationality. He argues the focus should be on the extraction of requirements from real-world conditions, rather than the

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Selection and peer-review under responsibility of Professor Lihui Wang.

treatment of already well-formed ones. In (4), he further argues for reflective iteration as a learning tool, and elaborates on the difficulty of treating and directly creating explicit knowledge, without taking the tacit dimension into consideration.

2.1. SECI-model and Knowledge in Product Development

In (5), the theory of "Organizational Knowledge Creation" is proposed as the capability of a company as a whole to create new knowledge, as a result of studying the success of certain Japanese companies. This is further elaborated in (6) by establishing the SECI-model of dynamic knowledge transfer and creation. The SECI-model spirals through the stages of Socialization (tacit-to-tacit), Externalization (tacit-to-explicit), Combination (explicit-to-explicit) and Internalization (explicit-to-tacit). Through these stages, tacit and explicit knowledge are transferred alternately. To quote the original authors; "When tacit knowledge is made explicit, knowledge is crystallized". Thus, in a learning perspective, the most interesting stages of the SECI-model are those transferring explicit to tacit knowledge, or vice versa (i.e. Externalization and Internalization), when considering individuals. Additionally, transferring tacit to tacit knowledge (i.e. Socialization) is interesting when considering groups.

Another contribution of (5, 6) is the establishment of knowledge assets, which are Experiential (e.g. individual skills, interpersonal relationships), Conceptual (e.g. product concepts, images), Routine (organizational routines, culture) and Systemic (e.g. documents, databases, patents). The study performed in (7) concludes Conceptual knowledge assets to be the most efficient tool in facilitating Internalization and Externalization. They are defined as "knowledge articulated through images, symbols and language" (6), and although not specified in the definition, this can be understood to include sketches and physical models.

2.2. The Concept of Affordance

The concept of 'affordance', first introduced by Gibson (8, 9), describes the relation between an object and the actions that an animal could perform as a result of this object's properties. This was slightly modified by Norman (10), who stated that "the term affordance refers to the perceived and actual properties of the thing, primarily those fundamental properties that determine just how the thing could possibly be used". The latter definition has gained major traction within certain product design communities. Despite some confusion around the use (and misuse) of the term in certain product design communities (11), the term is most often used as for describing physical objects and their meanings.

When using the term prototype affordance to describe both physical attributes and meanings of a product in engineering design, it is useful to make the distinction between prototype affordance and semantics (12). We differentiate between object meaning in prototype

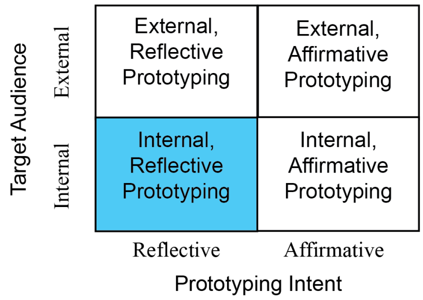

Figure 1 - A model of four prototyping categories (14).

affordance and semantics, as affordances cover all perceivable information provided by the object itself. On the other hand, the semantics cover perceived (and user-processed) product meanings provided by the object and context. Hence, prototype affordance – in our setting – is all the physical properties and all information embodied in the given object, before any interpretation (i.e. in SECI-model; internalization) is done by the participant.

2.3. The Role of Prototypes in Learning Activities

In (13), prototypes are defined as "an approximation of the product along one or more dimensions of interest", and prototyping is defined as "the process of developing such an approximation of the product".

For the purpose of distinguishing between prototyping activities by their function, the authors propose categories in (14), dividing prototypes by the prototyping intent (reflective or affirmative) and the target audience (internal or external). The referenced work is focusing on physical prototypes, while this paper is focusing on the prototyping activity. However, we argue that the categories are transferable (Figure 1).

External, affirmative prototyping is typically used for approximating a nearly finished model, and may be termed alpha or beta prototypes (15). These prototypes are highly detailed, and may be made for external validation (e.g. certification test for customers etc.), showcasing, or in-depth customer interaction.

Internal, affirmative prototyping is intended for function, reliability and feasibility testing. Examples include subsystems, fatigue testing of separate parts, or project milestones as a means of measuring the progress. Despite the high fidelity this prototyping is rarely done for public display.

External, reflective prototyping is building models for feedback from external sources. The responses and reactions are recorded, and the user interaction is carefully observed for further improving the concepts.

Internal, reflective prototyping is a learning activity. It is applied by product development teams for learning and conceptualizing ideas. This category of prototyping is exploring, understanding and experimenting with functionalities essential for the final product's success. The low-fidelity nature of the prototypes means there is less investment in the idea for the originator, and there is a relatively low threshold for criticism, change, or discarding.

Examples of internal, reflective prototyping are sketching and low-fidelity physical prototyping. This has been used in several industry cases (14).

Former studies have shown interaction with physical prototypes during idea generation to yield better performing designs than those only interacting with sketches (16). In addition, physical models contribute the most to the acquisition of knowledge (i.e. learning) (17). However, sketching during idea generation is argued in (18) to be the quickest way for designers to influence each other's mental models.

Both low-fidelity physical prototyping and sketching fall under the category of internal reflective prototyping. Thus they illuminate the distinction between high affordance internal, reflective prototyping (i.e. physical modelling) and low affordance internal, reflective prototyping (i.e. sketching).

2.4. Design fixation in requirements elicitation

In (19), design fixation is defined as "a blind adherence to a set of ideas or concepts limiting the output of conceptual design". That is, fixation on examples, and the inhibiting effect it has on further idea creation. Several studies have been made to examine attainable measures for minimizing design fixation. Some suggested solutions to design fixation are incubation (20) and design-by-analogy (21). Function trees have been shown to yield less design fixation than sketching (22), and what has been coined "the preference effect" shows that people fixate on their own ideas at the expense of those shared by others (23).

With respect to requirements elicitation, we apply terminology from the tacit knowledge framework (24, 25), using the terms "knowns" and "unknowns". The reflective prototyping categories aim at exploration, thus uncovering the unknown problems/concepts – the 'unknown unknowns' (i.e. non-articulated problems with unknown solutions). Coming from this perspective, we argue that known problems/concepts are best discovered analytically, while unknown problems/concepts are best solved exploratory.

A positive effect of testing physical models in mitigation of design fixation has been shown in (26). The studies made in (28, 29), both done with industrial design students in groups, conclude sketching to be the best representation aid for originality in the designs made during idea generation, while physical modelling yields more functional designs. Thus, indicating there is more design fixation involved when doing physical modelling than sketching, and that testing the physical models reduces fixation.

The role of the "sunk cost effect" (29) explains this by pointing out the investment in the design made by the designer, i.e. the more time and effort put into a concept, the less likely a designer is to discard it. With respect to the "sunk cost effect" one would assume a correlation between affordance and design fixation. However, studies have been done comparing sketching (i.e. low affordance) and physical modelling (i.e. high affordance), with no sign of this correlation (16, 30). A possible explanation is raised in (30).

	EVALUATION ROUND		ITERATIVE DESIGN ROUND	
TIME	t = 15 min.		t = 30 min.	
AFFORDANCE	HIGH	VS. LOW	HIGH	VS. LOW
TOOLS USED	PRE-MADE PHYSICAL PROTOTYPES	PRE-MADE ISOMETRIC DRAWINGS	PROTOTYPING BUILDING KIT	SKETCHING EQUIPMENT
DESIGN TASK	EVALUATE CONCEPTS AND WEIGH ATTRIBUTES		ITERATE AND IMPROVE CONCEPTS	
HYPOTHESES	PROBLEM AND CONCEPT UNDERSTANDING		DESIGN FIXATION	LEARNING ACTIVITY

Figure 2 – Proposed experimental scheme.

The "sunk cost effect" suggests designers are more devoted when a significant amount of effort is put into a design. The controlled studies (16, 30) had shorter time for idea generation and building than the studies done by observing real teams (27, 28), and consequently may not have had time to be sufficiently invested.

Further, the controlled study in (16) is evaluating the designs of groups and nominal groups (i.e. results from individuals completing the experiment put together in nominal groups after completion). The study concludes the ordinary groups to fixate more than the nominal groups. Thus, indicating that designers in groups – while able to build upon each other's ideas and creating more functional concepts – also fixate more.

2.5. Hypotheses

Grounded in this theory, and with the aim of exploring the impact of altering prototyping affordances during early stage engineering design activities, we propose three hypotheses; the Problem and Concept Understanding Hypothesis, the Design Fixation Hypothesis and the Learning Activity Hypothesis.

2.5.1. Problem and Concept Understanding Hypothesis

Based on the framework around internal, reflective prototyping, we aim to gain a better understanding of prototype affordance and how this affects the participants' ability to evaluate concepts. Hence, the hypothesis is:

Interaction with high affordance prototypes will lead to greater problem and concept understanding (during concept evaluation) than interaction with low affordance prototypes.

2.5.2. Design Fixation Hypothesis

Further, based on the framework around internal, reflective prototyping and design fixation, we aim to gain a better understanding of how prototype affordance affects the participants' fixation when designing. This translates into:

Prototyping with high levels of affordance will lead to more fixation (when designing) than prototyping with low levels of affordance.

2.5.3. Learning Activity Hypothesis

Lastly, based on the framework around internal, reflective prototyping as a learning activity, we aim to gain a better understanding of how prototype affordance affects the participants' learning outcome when designing:

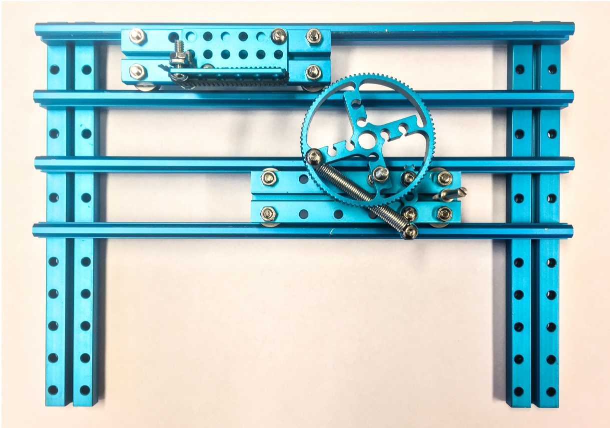

Figure 3 - Example of a high affordance prototype.

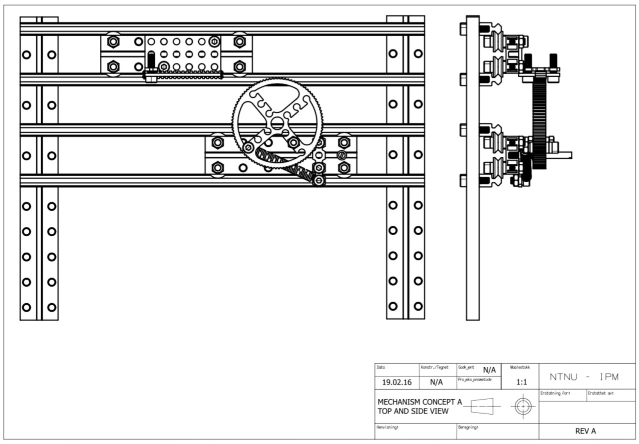

Figure 4 - Example of a low affordance prototype.

Prototyping with high levels of affordance will lead to higher quality designs than prototyping with low levels of affordance.

3. Proposed Experimental Setup

The hypotheses stated in the previous section will be evaluated in a proposed design experiment (Figure 2). This section is devoted to elaborating said experiment. The evaluation of the hypotheses is divided into a two-part controlled experiment setup. All participants are randomly assigned to either of two conditions, also describing the kind of internal, reflective prototyping activity they will be using for the duration of the experiment: ‘Low Affordance’ and ‘High Affordance’.

When starting the experiment, all participants are handed the initial problem definition. This problem definition is stated as a written text, together with a requirement specification and an illustration. As we are working with a global automotive tier 1/2 supplier, our initial problem definition is mechanical, and closely related to problems the participants might face in everyday engineering design activities.

As we are interested in the participants’ problem and concept understanding, and their ability to utilize this understanding, the experiment consists of two subsequent tasks. The first task is to do a round of concept evaluation, where participants are asked to evaluate a number of pre-defined concepts, all trying to satisfy the initial problem requirements. This task is referred to as ‘evaluation round’. The second task is to re-iterate a new and improved design, still based on the initial problem requirements. Lastly, the participants are asked to pick one concept, and finalize this for expert evaluation at the end of the second task. The second task is referred to as ‘iterative design round’.

3.1. Participants

The experiment is intended for automotive engineers who are experienced in the field of product development. The participants are expected to be familiar with concept evaluation and generation. There will be a minimum of 12 participants per independent variable ($N \geq 24$). Prior to the experiment, experimental pilots have been run, with mechanical engineering students as pilot participants.

3.2. Tools, Equipment and Materials

All participants, regardless of group assignment, are given an identical copy of the initial problem definition. Each copy includes a written problem text, a specification stating the requirements of the designs, and an illustration of the problem. As the group conditions also describe the affordance of the internal, reflective prototyping equipment they will be using throughout the experiment, the two groups will be provided slightly different equipment in each round.

Prior to the experiment, four concepts have been made according to the initial problem definition, and these will be used in the evaluation round. All four concepts are represented by both low and high affordance prototypes. The high affordance prototypes (Figure 3) are physical models, made in a modular, aluminum building kit (MakeBlock™). All pre-made concepts are based on a mechanical test rig, which includes two linear rails and two mounting brackets – interfaces used in the design task. This rig is made from the same building set. The low affordance prototypes (Figure 4) are represented by multiple isometric drawings, which are drawn using the high affordance prototypes for reference.

During the evaluation round, all participants are asked to fill out a Pugh-diagram (i.e. evaluation matrix), containing pre-selected evaluation criteria. Normally, Pugh charts contains weighted categories, but as the aim of the evaluation round is to check both problem and concept understanding, this weighing is left blank for the participants to fill out. A short description on using the Pugh-diagram is provided along with the task description, though it is expected that all participants are familiar with the diagram prior to the experiment.

During the iterative design round, participants under the low affordance condition will be given lower affordance tools while iterating their new designs, here represented by standard sketching tools (i.e. squared paper, pen, pencil, ruler, eraser, protractor, compass). Conversely, participants under the high affordance condition will be given higher affordance tools, represented by the same anodized aluminum building kit as in the evaluation round. The participants under the high affordance condition are also allowed to use and interact with the high affordance prototypes for the duration of the experiment.

During the finalizing of the concepts in the iterative design round, all participants (regardless of group condition), will be handed the same tools, including a pre-made rig for testing the mechanical interface of the concepts. This way, both groups will use more time on assessing critical functionality of their designs.

To make the experiment as realistic as possible, the experiment area is set in a standard meeting room, with a centered medium-sized table and office chairs. The room is closed off to any persons not taking part in or running the experiment. Before each participant enters the experiment area, the room layout is reset, and all necessary tools and equipment are laid out on the table surface. The experimental area is equipped with video-cameras, as the participants will be filmed for the duration of the experiment. There is also a dedicated camera for filming the participants' final concept presentations after the iterative design round.

3.3. Proposed Experimental Procedure

Before starting the experiment, all participants are greeted and welcomed into a waiting area. Here, they are asked to fill out a consent form and told that further communication during the experiment will be provided in written text. The participant is given the initial problem definition handout, and is given five minutes to read and contemplate on the problem. When the participant is handed the initial problem definition, the experiment is considered as running, with only one participant at a time.

3.3.1. Evaluation Round

After the first five minutes of reading, the task description for the evaluation round is handed out, along with an empty pre-made Pugh-diagram for evaluating the different concepts. The pre-made concepts are thereby presented, with level of affordance according to group condition. Participants are given fifteen minutes for evaluating the pre-made concepts, after which they are asked to hand in the complete Pugh-diagram.

3.3.2. Iterative Design Round

Upon handing in the Pugh-diagram, each participant will be handed the task description for the iterative design round. In addition, each participant will get prototyping equipment according to their group condition. Each participant is given twenty minutes to improve and iterate a better design than the four previous concepts. After these 20 minutes, all participants (regardless of group condition) are handed a physical prototyping kit, and get instructions to finalize a conceptual prototype for evaluation. Finally, each concept is handed in for external evaluation. This is done by each participant getting to record a two-minute demonstration in a video-log format.

3.4. Proposed Metrics for Evaluation

In this section, we will cover the necessary steps in gathering metrics for evaluating the three stated hypotheses. This includes both definition and quantification of all variables. In this experiment, we are using three expert ratings, somewhat similar to what has been done in (16, 31).

3.4.1. Independent Variables

For all three hypotheses, the independent variable is prototyping affordance. As we do not intend to quantify this beyond stating that we are using high and low levels of affordance, this is a categorical variable, with two discrete conditions. Note that we differentiate between high/low affordance prototypes (i.e. objects) and high/low affordance prototyping (i.e. activities). However, the independent variable is the level of affordance being used, we view this as the same independent variable for all practical purposes.

3.4.2. Dependent Variables

For the problem and concept understanding hypothesis, we include two dependent variables; 'problem understanding' and 'concept understanding'. Both variables are measured by using an expert ranking system, getting three independent experts ranking the pre-made concepts in the same Pugh-diagram as the participants. The experts' ratings of weighted categories are used as a baseline for the 'problem understanding' variable, and the ratings of each specific concept is used as baselines for the 'concept understanding' variable. Each participant's deviation is compared to the experts' combined baseline, indicating the participant's level of (problem and concept) understanding. We argue that by observing this deviation, we can extrapolate whether or not the participants have sufficient understanding of each concept.

To test the design fixation hypothesis, the number of neutral and negative fixation features present, in each of the finalized conceptual prototypes (after the iterative design round), is identified by three independent experts. These neutral and negative fixation features are based on the pre-made concepts, thus giving a measure of how fixated the finalized conceptual prototypes are.

For the learning activity hypothesis, we are using 'quality of design' as the dependent variable. This variable is quantified by using the same independent expert ranking (i.e. using the same Pugh chart), and comparing the finalized conceptual prototype to the pre-made concept prototypes. Here, the 'quality of design' variable is defined as the deviation from the pre-made concepts, where positive deviation indicates better quality, and negative deviation indicates lower quality than the experiment baseline.

4. Discussing the Proposed Experiment

As this paper aims at proposing an experimental setup, we are aware of several limitations that may apply. We have chosen to focus our efforts on exploring how affordance will affect learning outcome. Therefore, we are using the same two group conditions for each of the rounds. One could argue that, to do a more thorough evaluation of the hypotheses, we could divide the groups after the evaluation round, and arrange participants from each condition into new conditions for the iterative design round. This has been avoided, mostly due to the experiment being aimed at a professional company setting. Therefore, the number of participants available is somewhat limited.

Also, one can argue that participants who are using the high affordance prototyping kit during the whole experiment have a major advantage when finalizing designs in the second round. We try to mitigate this effect by giving all participants a pre-assembled testing rig, making the gap between low and high affordance as small as possible.

We are dealing with professional participants from a real engineering design setting, and hence there will be an effect from pre-experiment biases, difference in experience and other considerations not taken into account.

5. Conclusion

In this paper, attempts have been made to understand learning and learning activities within product development (both individual and organizational), and the influence of the concept of affordance on learning outcome. With this in mind, roles of different prototyping categories have been presented, with emphasis on internal, reflective prototyping as a learning activity.

Furthermore, the article has proposed an experimental setup and procedure to test three hypotheses: a hypothesis on concept and problem understanding; a hypothesis on design fixation; and a hypothesis on learning activity outcome. A framework for evaluating said hypotheses is presented, complimented by some considerations on the limitations of this experiment. Initial piloting of the experiment has begun, and early piloting indicate that high affordance prototypes may lead to both more problem and concept understanding.

Ultimately, this experiment is intended for professional practitioners in engineering design, and we hope this will help understand the learning mechanisms of internal, reflective prototyping in a real-world setting.

Acknowledgements

This research is supported by the Research Council of Norway through its user-driven research (BIA) funding scheme, project number 236739/O30.

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Research Paper III

Prototyping to Leverage Learning in Product Manufacturing Environments

Erichsen, Jorgen A. B., Andreas Lyder Pedersen, Martin Steinert, and Torgeir Welo. “Prototyping to Leverage Learning in Product Manufacturing Environments.” Procedia CIRP, June 2016. doi:10.1016/j.procir.2016.04.099.

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6th CLF - 6th CIRP Conference on Learning Factories

Prototyping to Leverage Learning in Product Manufacturing Environments

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Abstract

Rooted in the automotive industry, this article discusses the topic of leveraging tacit knowledge through prototyping. After first providing an overview on learning and knowledge, the Socialization, Externalization, Combination and Internalization (SECI) model is discussed in detail, with a clear distinction between tacit and explicit knowledge. Based on this model, we propose a framework for using said reflective and affirmative prototyping in an external vs. internal learning/knowledge capturing and transfer setting. Contextual examples from select automotive manufacturing R&D projects are given to demonstrate the importance and potential in applying more effective strategies for knowledge transformation in engineering design.

Peer-review under responsibility of the scientific committee of the 6th CIRP Conference on Learning Factories.

Keywords: knowledge transfer; internal reflective prototyping; prototyping; tacit knowledge; integration events; product development

1. Introduction and Background

In this article, we argue for the use of explorative and analytical approaches in product development processes by discussing tacit knowledge accumulation and transfer through prototypes. With this intention, we attempt to make several contributions to current literature.

Firstly, we present a mapping of relevant literature on the topic of knowledge, especially related to product development. In this section, we are exploring organizational and individual knowledge, the differentiation of tacit and explicit knowledge, in addition to some current practices on the transfer of (tacit) knowledge.

The second contribution is to present a model of prototyping categories, with special emphasis on the differentiation between learning and verification as the main intent for prototyping activities. A model of four prototyping categories is proposed, and discussed in relation to dealing with known and unknown problems concerning tacit knowledge in product development.

The article closes by exemplifying the previous two sections by providing insights from two industry cases. The use of analytical and explorative approaches to prototyping are discussed, and several possible research opportunities are presented.

The automotive industry—an industry with steadily increasing demand for faster development cycles and higher quality products—is subject to increasing competitive pressure. Making mistakes is costly in an industry where product life cycles are in the order of five to ten years, and late-stage design changes have major implications for manufacturing planning and processes. In addition, automakers need to rely on previous experience, and cannot start from scratch in each development project. The use of process and part standardization within the product technology platforms is a well-established practice to reduce the burden on the development teams. Hence, much research is currently targeting knowledge and learning mechanisms in new product development. Examples include knowledge-based development (1)—a method for extracting basic principles of Toyota's product development processes (2).

In this paper, we focus on analytical and explorative approaches, and their relation to both creation and transfer of tacit knowledge in product development.

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Peer-review under responsibility of the scientific committee of the 6th CIRP Conference on Learning Factories.

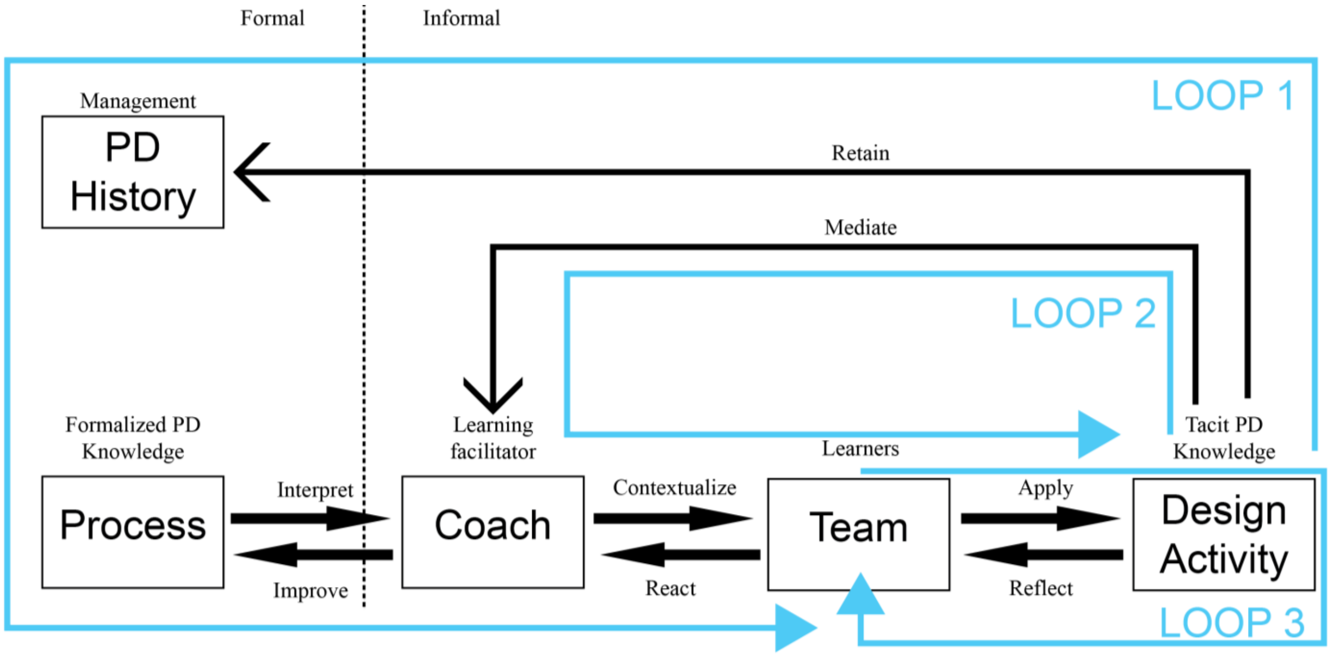

Figure 1 - Learning mechanisms in product development, adopted from (9) and (10).

2. Theory: Knowledge in Product Development

In (3), Ulonska presents numerous definitions of knowledge found in product development. Rowley differentiates knowledge and wisdom (4) by defining knowledge as application of data and information ("know-how"), whereas wisdom is defined as elevated understanding ("know-why"). Additionally, it can be argued that knowledge can be further divided into individual and organizational knowledge (5). The sum of what is learned, experienced, discovered or perceived (by individuals) during a project (in the organization) defines organizational learning. The interactions of individuals are the main ingredients of organizational knowledge, and the knowledge of these individuals is called individual knowledge. This is categorized in three categories; experience-based, information-based and personal knowledge (6). Nonaka and Takeuchi argue that the organizational knowledge exists between (and not within) individuals (7).

2.1. Defining Integration Events and Knowledge Owners

Most product development organizations use stage-gates for decision making. The stage-gate model is a financially-based governance method, which leverages the importance of financial decisions during development. However, this type of process governance often makes event-based technological decisions harder. Hence, there is a call for a more event-based governance model in product development (8). An example on such events can be the emerging trend of hosting 'integration-events'. These events are so-called learning cycle gates, and aim at ensuring better insights and information while preserving previous project know-how and learnings. This way, large product development organizations aim at transferring project (individual) knowledge into organizational learning. Here, informal knowledge is formalized (made explicit), and formal knowledge is interpreted (by the individuals). The key to successful organizational learning is a mutual exchange of these two kinds of knowledge.

Some companies employ key experts or learning facilitators as catalysts for the exchange of knowledge within their organization. These so-called knowledge owners are usually technical or functional managers, who help preserve and facilitate the learnings and insights. Examples of key experts are Toyota's functional managers who owns the technology. The functional managers employ existing knowledge within projects, while so-called chief engineers challenge the existing standard by being the customer representative. By spending time with and on the development team, these key experts gain experience and insights, which in turn will contribute to organizational learning inside the company.

By taking a closer look at learning mechanisms in product development in Fig. 1—first introduced by Eris and Leifer (9), and then further iterated by Leifer and Steinert (10)—the distinction between formal and informal knowledge is clarified. Key experts are usually working in the informal area (i.e. learning loops two and three), whereas the organization as a whole operates in the formal area (i.e. learning loop one).

2.2. Tacit and Explicit Knowledge in PD

The terms tacit and explicit knowledge are closely linked to formal and informal knowledge. Explicit knowledge consists of information, facts and numbers that have been formalized (learning loop one from Fig. 1) (11), and they can be summarized into so-called 'knowledge artifacts' (12). Examples on these knowledge artifacts include the widespread use of A3 sheets in the Toyota product development system (2,13), which usually contain condensed explicit information about a project or system. Tacit (or informal) knowledge includes everything non-explicit, hereunder learnings, know-how, craft and skill of the product engineering individuals, accumulated in learning loops two and three (14). We argue that one key dimension of tacit knowledge is the interaction with (and use of) objects and experiences in the product engineering processes, often referred to as prototypes in one form or another.

2.3. The SECI-model and Transfer of Knowledge in PD

First proposed by Nonaka, Toyama and Konno (15) as a prevalent model for enhancement of knowledge creation through conversion of tacit and explicit knowledge, the SECI process (Fig. 2) can be used for describing the different stages of knowledge transfer. The SECI model consists of four stages, including socialization, externalization, combination and internalization, and is used to describe how various knowledge is transferred (in an organization) by spiraling through the four stages. Four knowledge assets are presented as facilitators of knowledge creation, and are categorized as experimental, conceptual, systemic and routine. The latter has gotten increasing support since its first appearance, and a study by Chou and He (16) concludes conceptual knowledge assets (i.e. PD insights) to have the most effect on knowledge creation.

By further studying the model, we can categorize the three stages socialization (tacit-to-tacit), internalization (explicit-to-tacit) and externalization (tacit-to-explicit) as forms of either creation or transfer of tacit knowledge in development teams. The last stage, combination (explicit-to-explicit), can be described as an implemented knowledge repository, where the formalized knowledge within the organization might be distributed to sub-groups that require this knowledge. In the context of transferring tacit knowledge, socialization includes creating a work environment that encourages understanding of expertise and skills through practice and demonstrators. Externalization, or the act of formalizing the tacit knowledge, aims at feeding this into the organization. Similarly, internalization aims at interpretation of formal knowledge, and includes conducting experiments, sharing results, and facilitating prototyping as a means of knowledge acquisition (15). Chou and He (16) also conclude that conceptual knowledge assets—i.e. “knowledge articulated through images, symbols and language” (15)—are the most efficient tool for facilitating externalization and internalization.

2.4. A Proposed Model of Prototyping Categories

In (17), prototypes are defined as “An approximation of the product along one or more dimensions of interest”, thus including both physical and non-physical models. Examples include (but are not limited to) sketches, mathematical models, simulations, test components and fully functional pre-production versions of the concept (18).

We argue that prototyping can be divided into four different categories (Fig. 3) (19). The horizontal axis—the intent of the prototype—is split into two sub-categories; “reflective” and “affirmative”. The vertical axis, displaying the target audience of the prototype, is spit into “internal” and “external”. This two-by-two matrix gives four different prototyping categories which will be briefly explained below.

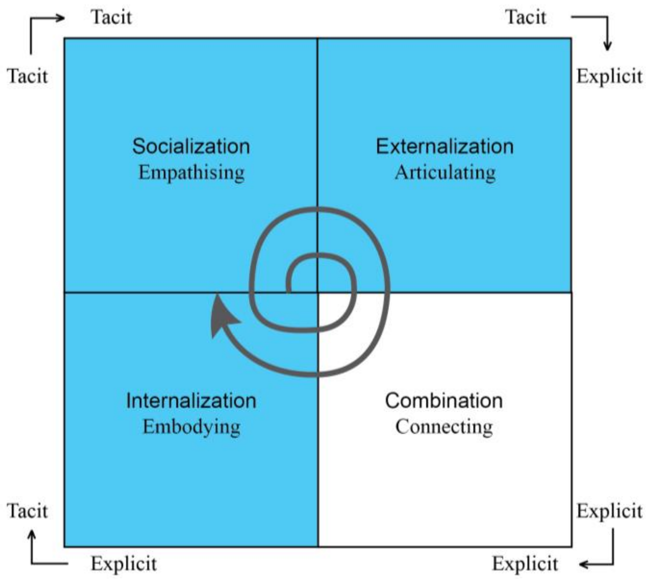

Figure 2 - The SECI-model, with blue areas highlighted as areas of interest, adopted from (15).

2.4.1. External, affirmative prototyping

Typically used for making pre-production models, this kind of prototyping approximate a nearly finished model, and are often termed alpha and/or beta prototypes (20) intended for validation or showcase purposes. These prototypes are high fidelity (i.e. highly detailed) models, used for external validation (e.g. certification test etc.), marketing, or in-depth customer interaction. In an automotive setting, these may be the cars subject to road testing, being pre-production cars tested on closed test circuits by external users.

2.4.2. Internal, affirmative prototyping

Focused in terms of function, this type of prototyping is intended for function, reliability and feasibility testing. Examples include combinations of subsystems, fatigue testing of conceptual prototypes or project milestones to validate team progression. Although high in fidelity (regarding function and complexity), these prototypes are still rarely shown to public audiences. Automotive examples on this kind of prototyping includes running lifecycle testing of components, like shock absorbers, axles and other moving parts.

2.4.3. External, reflective prototyping

Companies often seek feedback from external sources by showing off concepts. User interaction is carefully observed and recorded for further study, and responses and reactions are used for further improving other concepts. This kind of prototyping is used for observing interaction with external sources, enabling the design team to take a step back and learn from the observations. In the automotive industry, automakers often show off one-of-a-kind concept car projects at large automotive venues to gather external feedback and reactions.

2.4.4. Internal, reflective prototyping

Internal, reflective prototyping is a learning activity, used by the product development team to learn and conceptualize ideas. These prototypes are rough, made for exploring, understanding

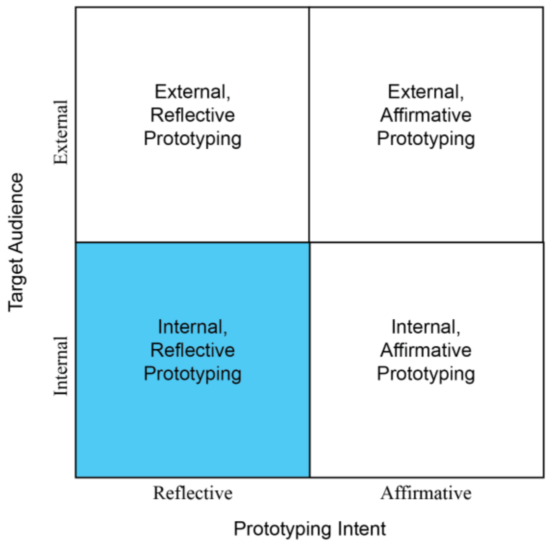

Figure 3 - A proposed model of four prototyping categories.

and experimenting with functionalities that are essential for product success, with the aim of creating new insights within the product development team (21). Typically, internal, reflective prototypes have low fidelity (22), and therefore regarded as waste after a project is finished. These prototypes may prove especially useful when facing high complex problems, like the component layout of an automotive engine bay.

By using terminology from the Tacit Knowledge Framework (23,24), we use the terms 'knowns' and 'unknowns'; Both affirmative prototyping categories are linked to analysis, as they are dealing with known problems and requirements—the 'known knowns' (i.e. known articulated problems with known possible solutions). Adversely, reflective prototyping categories aim at exploration, and thus at dealing with unknown problems—the 'unknown unknowns' (i.e. non-articulated problems with unknown solutions). Coming from this perspective, we argue that known problems are best solved analytically, while unknown problems are best solved exploratively.

3. Examples: Learning from Prototyping

In the following subsections, the theory presented in the previous section will be accentuated to show the influence of internal, reflective prototyping in product development. The first case considers applying a physical prototype to an analysis for evaluating the numerical method and consequentially learning about the method and saving time in the process. The second case presents a failed crash box, once designed for a new car model that was well analyzed—but still failed due to an overlooked design-manufacturing detail. A discussion of the mistakes is made in light of the theory presented.

3.1. Case I: Applying Physical Computation for a Rotational Spiral Spring

In (25), a case illustrates the effects of combining numerical computations with testing a physical representation of the design. The time required to design a concept by using

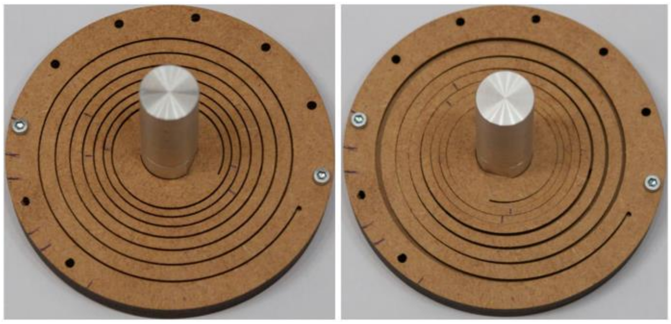

Figure 4 - MDF prototype with markings used to estimate the flex of the rotational spring (25).

analytical tools in complex cases can be greatly reduced by applying a physical prototype for testing and comparison, as proposed in the article.

The case studies a rotational spiral spring that is analyzed by setting up a numerical model (using mechanical spring theory), predicting stiffness and maximum stress of the rotational spiral spring. Meanwhile, a physical model is made with MDF (Medium Density Fibreboard) and tested (Fig. 4). The output data reveals a striking similarity, though the stiffness is somewhat overestimated in the analysis. Although the results are not identical, the combination of the physical and numerical computations shows the numerical analysis to be transferable to the physical dimension and may be scaled further. Combined, these methods yield satisfactory results in a very short time.

This case shows very well how time can be saved by applying internal, reflective prototyping early in the product development process to facilitate faster learning. This approach may prove especially applicable for complex cases, reducing complexity by understanding which analytical tools might be appropriate—and saving time by doing so. As for all internal, reflective prototyping, the prototype used for the physical part of the computation is not applicable in the finished product. However, it facilitates the designers' learning of how their analytical problem transfers into the physical domain. Internal, reflective prototyping is used to learn from internally, either individually or as a collaborative group, as they typically are low fidelity in nature, but educational and time saving.

3.2. Case II: Crash Box Failure Due to Lack of Variability Testing

In this case, we use an example from a large European automaker, which had designed a crash box for topological optimization, to be fit into a new car model. Crash boxes, separate deformation elements between the front bumper and the front longitudinal rail, are designed to deform on low-speed impact to prevent damage to the rest of the car to reduce the repair cost. The production method of the crash box was extrusion of one open cross-section that was bent, cut, pierced, and welded into a closed box configuration with an integrated foot plate mounted to the rails.

The Danner crash test (26) rates cars at the impact of collision in their ability to minimize costs of repair at 0-15km/h, for the purpose of evaluating the car's properties to set an insurance premium base. In the Danner test, the crash box

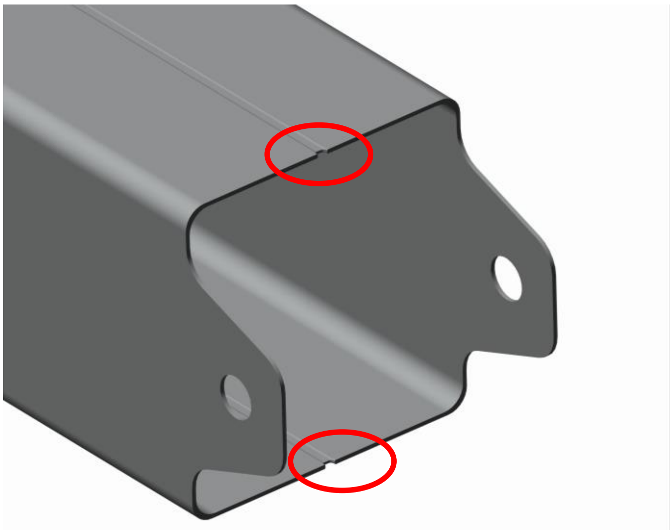

Figure 5 - Exemplification of a crash box, with highlighted area of interest.

of the said model was expected to crush in a controlled manner upon collision test impact without damaging expensive components or activate the air bags, which are the costliest to replace. In the numerous FEA simulations done to optimize the system, the welding configuration was assumed to be geometrically perfect, starting at the very end of the box. However, in production (MIG) welding, start and stop of the weld seam tend to create minor groove of varying magnitude at the very end, depending on dimensional accuracy of the individual part, and other control parameters. Hence, the accuracy of the FEA model was not capable of capturing the local stress state in the vicinity of the grove (as illustrated in Fig. 5). Instead of failing by controlled crushing as predicted in the FEA model, occasionally, the weld seam failed like a zipper starting from the very end of the box once the bumper folded and contacted the very end of the crash box. The fluctuations (in the force deformation curve) triggered the air bag sensors, resulting in the airbags deploying in low speed tests at 15 km/h. This type of failure is considered catastrophic as a consequence of the repair costs associated with replacing the airbags.

The influence of small variations imposed by manufacturing (welding) is a very complex matter. Sensitivity testing of the crash box with the same production-intent premises as the serial produced product would have prevented encountering a failure such a long time after launch. This clearly demonstrates the risk of failing to integrate the product development process and the manufacturing process. The design engineers did not know this would be an issue, and the unspecified 'parameter' related to end configuration (of the weld) remained an unknown until several vehicles were retested after launch.

If the team had engaged in internal reflective prototyping activities, the influence of such critical design features could have been uncovered. The learning outcome in this case could have led the team members to acquire the necessary knowledge to see the disconnection between the manufacturing process and the intended design, possibly identifying a low-cost solution (process or design change) to such a fairly fixable problem.

In this case, properly done internal, affirmative prototyping could have uncovered the problem. However, we would argue that doing internal, reflective prototyping in the early stages of the development process would have facilitated important learning. As a result, the early development process would be less complex, and problems not otherwise perceived as problems would be uncovered. Hence the value of prototyping and testing to learn—not only to verify—could have significantly saved time, money and averted the ultimate failure of the design.

4. Research Potential of Using Explorative and Analytical Methods for Learning in Product Development

Furthermore, the insights, experience and learnings present a unique research opportunity, since improved understanding of the creation and transfer of tacit knowledge will alter how we facilitate the product development process. Hence, there is a call for more research concerning how tacit knowledge influences the development of products with high levels of complexity, especially when dealing with many unknown unknowns.

As identified in (27), there is a gap between professional knowledge and real-world practice. In his works, Simon applies methods of optimization from statistical decision theory, thus laying a foundation for a scientific approach to treating knowledge. Adversely, Schön (28) argues that the real challenge lies not within the treatment of well-formed requirements, but rather the extraction of such requirements—practically unknown unknowns—from real world situations. In (29), Schön presents reflective iteration rounds as a learning tool of great potential. Taking this perspective, we argue that reflective prototyping may be used as a learning tool in handling unknown unknowns in product development.

Ultimately, we argue that, in reality, product development requires balancing of the tacit and the explicit, the explorative and the analytical. We have seen that disconnection between product development and manufacturing processes cause major implications for entire value chains. In hindsight, exploration and experience of manufacturing techniques and challenges could have led to the discovery of potential risks and problems in the product development process (unknown unknowns), and—if so—how to best balance analysis and exploration for uncovering these unknowns in a cost and resource efficient manner?

5. Conclusion

The purpose of this paper has been to accentuate the possibilities of using prototyping in product development for manufacturing settings. An attempt has been made to map future opportunities, both for industry and academia, and a call for the recognition of prototyping as a time saving learning tool. The potential of applying exploration by interaction with prototypes related to knowledge capture, transfer and learning is demonstrated in the context of the automotive industry. Thus, a call for increased focus on mixing analytical (e.g. simulations) and explorative (e.g. prototyping) approaches is presented as a viable direction for further efforts in both industry and academic communities.

Altogether, the importance of understanding the interplay between (tacit) knowledge, explorative and analytical approaches to problems in product development and manufacturing, and the role of prototyping for learning are topics that require further pursuit.

Acknowledgements

This research is supported by the Research Council of Norway through its user-driven research (BIA) funding scheme, project number 236739/O30.

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Appendix A

Research Experiment Participant Handouts

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NTNU

Fakultet for ingeniørvitenskap og teknologi
Institutt for produktutvikling og materialer

Vår dato	Vår referanse
15.03.16	JABE
Deres dato	Deres referanse

Request for participation in research project

Background and Purpose

The purpose of this project is to 1) study current practice in a real-world industrial setting, and to 2) understand the mechanics of concept evaluation and iterative concept generation. This experiment is part of a Master's Thesis and a PhD at IPM, Norwegian University of Science and Technology.

What does participation in the project imply?

The participant will be asked to evaluate a select number of pre-defined concepts, and data from this evaluation will be stored. After being introduced to the task, the participant will be guided through the experiment. The experiment is comprised of two parts; Part I and Part II. The participant will be asked to fill out a questionnaire as part of the experiment.

What will happen to the information about you?

All personal data will be treated anonymously. No name is connected to the gathered data. The only persons having access to the data are the two master students and their supervisor. In case of a publication, participants will therefore not be recognizable. The project is scheduled for completion by 31.12.2018. After this date the personal data will be stored encrypted.

Voluntary participation

The participation of this experiment is voluntary, and you can at any time choose to stop and withdraw from the experiment. If you would like to participate or if you have any questions concerning the project, please contact Jørgen A. B. Erichsen (+47 416 46 804), Andreas L. Pedersen or Martin Steinert.

Consent for participation in the study

I have received information about the project and am willing to participate. I agree that data is collected, analyzed and published anonymously. I further agree to be confidential about the experiment to provide non-biased conditions for every participant.

Name of the participant (Please use capital letters)

Place & date, Signature

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Pilot Experiment, Part I (20 min)

Welcome, and thank you for participating!

In this session, we present a technical problem, along with a task for you to solve. Please follow the guide presented below. The provided materials are:

- This description sheet, including an empty evaluation matrix.
- A set of drawings of four proposed concept solutions A, B, C and D for the described technical problem.

Technical problem

The technical problem is comprised of a locking mechanism for two wagons, which are mounted on rails. The two wagons are both able to move freely in their own rails, but are prohibited from moving past each other by the locking mechanism. In addition, the locking mechanism is required to lock both wagons into each other in such a way that force can be transferred from the one wagon to the other.

This problem is an abstraction of a locking mechanism for a commercial car model. Hence, the system is subject to wear. Because of this, the locking mechanism needs to be adjustable in such a way that the two wagons can lock at different positions.

Task description

Please use the drawings of the four pre-made concepts that are provided, and evaluate these as solutions to the previously discussed technical problem. The deliverables for this task is given on page 3 of this document.

Each concept has two states; engaged and disengaged. In these abstractions, the engaging/disengaging of the locking mechanism is done by spring/hand, but in its' real-world application, the force will be applied by other means of mechanical actuation. Use the provided evaluation matrix and provided concept attributes, found on the next page.

You will get 20 minutes to finish your evaluation. Upon completion, please put your evaluation sheet in the designated "deliverables" folder. New instructions will be provided upon completion.

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Concept A

This concept is based on two stepped pieces locking when activated by a spring. Once engaged, the smaller sliding wagon can move forward only until meeting the step, but also backwards and slip down into a lower step. (See attached drawings)

Concept B

This concept is based on two pieces with teeth in the interface of the locking mechanism. Once engaged, the smaller sliding wagon is locked to the practically stationary wagon, and cannot move in either direction. (See attached drawings)

Concept C

This concept is based on an angled pointer interacting on a toothed face. Once engaged, the angle of the pointer makes the freely sliding wagon able to move backwards into a new position, but not forward. (See attached drawings)

Concept D

This concept applies long teeth in the direction of the rails. An engagement slider is activated by a spring to create friction between the teeth to lock them. Once engaged, this friction locks the wagons and the freely sliding wagon cannot move in either direction. (See attached drawings)

Physical attributes

Interface Friction – This is an indicator of how much friction the mechanism provides in the interface. A higher rating indicates higher friction.

Holding force – This is an indicator of the holding force in the interface. A higher rating indicates more holding force.

Disengaging Force – This is an indicator of the required force to disengage the interface. A higher rating indicates more force.

Stability – How stable is the mechanism? A higher rating indicates a more stable mechanism.

Complexity – How many parts/features are present? A higher number indicates more complexity.

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Evaluation Matrix

Grade each of the concepts A, B, C and D on a scale from 0 to 10 according to the presence of each of the listed attributes.

Physical Attributes	Concept A	Concept B	Concept C	Concept D
Interface Friction				
Holding Force				
Disengaging Force				
Stability				
Complexity				

Influence of Physical Attributes

How will the presence of these attributes affect the technical problem? Please mark one alternative per attribute.

	Very Negative	Negative	Slightly Negative	Neutral	Slightly Positive	Positive	Very Positive
Interface Friction	☐	☐	☐	☐	☐	☐	☐
Holding Force	☐	☐	☐	☐	☐	☐	☐
Disengaging Force	☐	☐	☐	☐	☐	☐	☐
Stability	☐	☐	☐	☐	☐	☐	☐
Complexity	☐	☐	☐	☐	☐	☐	☐

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Pilot Experiment, Part II (20 min)

You have now finished your evaluation, and thereby part I of the experiment. In the second part, you are now asked to utilize your experience from this evaluation, and propose an improved solution to the technical problem.

In addition to the provided materials of part I, your provided materials for part II are:

- This description sheet
- Drawing equipment
- Blank A3-sheets of printer paper
- Four technical drawings of the technical system, without locking mechanisms.

Task Description

Your task in this part of the experiment is to design an optimum solution to the technical problem provided in part I, using the drawing equipment provided. Please feel free to use as many of the sheets of A3 paper, including the technical drawings already provided.

You will get 20 minutes for completing this task. Upon completion, you will be asked to hand in as many sheets of A3 paper describing your optimum solution as you prefer.

Thank you for your time and participation, and good luck.

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Background Information Questionnaire

This questionnaire is designed to collect additional background information about you.

Part A. Education

The questions in this section are designed to collect information on your education.

A1. What is your current level of achieved education?

- ☐ High School
- ☐ College
- ☐ Bachelor's Degree
- ☐ Master's Degree
- ☐ Ph.D.

A2. When did you graduate?

Month ☐☐ Year ☐☐☐☐

A3a. Please record your primary area of specialization.

Primary Area
of Specialization: ____

A3b. Please record any additional areas of specialization you currently have.

IF NONE: MARK THIS BOX: ☐

1. Area of Specialization: ____

2. Area of Specialization: ____

3. Area of Specialization: ____

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A4. Are you currently studying for a degree? If no, skip to part B. If yes, please specify:

- ☐ High School
- ☐ College
- ☐ Bachelor's Degree
- ☐ Master's Degree
- ☐ Ph.D.

A5. When do you plan to graduate?

Month ☐☐ Year ☐☐☐☐

A6a. Please record your primary area of specialization.

Primary Area
of Specialization: ____

A6b. Please record any additional areas of specialization you currently have.

IF NONE: MARK THIS BOX: ☐

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3. Area of Specialization: ____

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Part B: Professional Experience

The questions in this section are designed to collect information on your career and whether and how they have changed over time. Please give estimates wherever suitable.

B1. For how long have you worked for a engineering company?

If you have never worked for any engineering companies: Skip to Part C.

Answer: ____

B2a. Where do you currently work?

If you have no current employer: Skip to B3

Company: ____

B2b. For how long have you worked for your current employer?

Answer: ____

B2c. Are you assigned to a specific department by your current employer?

☐ Management
☐ Research and Development (R&D)
☐ Testing and Verification
Other: ____

B3. For how long have you worked in the automotive industry?

If you have not worked in the automotive industry: Mark this box: ☐

Answer: ____

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Part C: Demographic Information

The questions in this section are designed to collect some of your demographic information.

C1. Are you:

☐ Male
☐ Female

C2. In what year were you born?

Year of Birth: ☐☐☐☐

C3. What is your nationality (i.e. citizenship)?
Please specify if you have multiple citizenships.

Answer: ____

Part D: Further Participation

D1. Are you willing to receive follow-up questions or surveys of this study via e-mail in the future? If yes, please write your e-mail address below.

E-mail address: ____

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Part E: General Information

You have just participated in an experiment on concept evaluation, containing elements of problem understanding, design fixation and a view into your learning gain from interacting with different concept representations.

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We wish to remind you to be confidential about the content of this experiment to provide non-biased conditions for every participant, as stated in the consent form. We hope you enjoyed participating, and thank you kindly for your commitment of time to this experiment!

Thank you for your time and participation!

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15.03.16	JABE
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Request for participation in research project

Background and Purpose

The purpose of this project is to 1) study current practice in a real-world industrial setting, and to 2) understand the mechanics of concept evaluation and iterative concept generation. This experiment is part of a Master's Thesis and a PhD at IPM, Norwegian University of Science and Technology.

What does participation in the project imply?

The participant will be asked to evaluate a select number of pre-defined concepts, and data from this evaluation will be stored. After being introduced to the task, the participant will be guided through the experiment. The experiment is comprised of two parts; Part I and Part II. The participant will be asked to fill out a questionnaire as part of the experiment.

What will happen to the information about you?

All personal data will be treated anonymously. No name is connected to the gathered data. The only persons having access to the data are the two master students and their supervisor. In case of a publication, participants will therefore not be recognizable. The project is scheduled for completion by 31.12.2018. After this date the personal data will be stored encrypted.

Voluntary participation

The participation of this experiment is voluntary, and you can at any time choose to stop and withdraw from the experiment. If you would like to participate or if you have any questions concerning the project, please contact Jørgen A. B. Erichsen (+47 416 46 804), Andreas L. Pedersen or Martin Steinert.

Consent for participation in the study

I have received information about the project and am willing to participate. I agree that data is collected, analyzed and published anonymously. I further agree to be confidential about the experiment to provide non-biased conditions for every participant.

Name of the participant (Please use capital letters)

Place & date, Signature

Andreas L. Pedersen　　　Jørgen A. B. Erichsen

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Pilot Experiment, Part I (20 min)

Welcome, and thank you for participating!

In this session, we present a technical problem, along with a task for you to solve. Please follow the guide presented below. The provided materials are:

- This description sheet, including an empty evaluation matrix.
- A set of physical models of four proposed concept solutions A, B, C and D for the described technical problem.

Technical problem

The technical problem is comprised of a locking mechanism for two wagons, which are mounted on rails. The two wagons are both able to move freely in their own rails, but are prohibited from moving past each other by the locking mechanism. In addition, the locking mechanism is required to lock both wagons into each other in such a way that force can be transferred from the one wagon to the other.

This problem is an abstraction of a locking mechanism for a commercial car model. Hence, the system is subject to wear. Because of this, the locking mechanism needs to be adjustable in such a way that the two wagons can lock at different positions.

Task description

Please use the models of the four pre-made concepts that are provided, and evaluate these as solutions to the previously discussed technical problem. The deliverables for this task is given on page 3 of this document.

Each concept has two states; engaged and disengaged. In these abstractions, the engaging/disengaging of the locking mechanism is done by spring/hand, but in its' real-world application, the force will be applied by other means of mechanical actuation. Use the provided evaluation matrix and provided concept attributes, found on the next page.

You will get 20 minutes to finish your evaluation. Upon completion, please put your evaluation sheet in the designated "deliverables" folder. New instructions will be provided upon completion.

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Concept A

This concept is based on two stepped pieces locking when activated by a spring. Once engaged, the smaller sliding wagon can move forward only until meeting the step, but also backwards and slip down into a lower step. (See attached model)

Concept B

This concept is based on two pieces with teeth in the interface of the locking mechanism. Once engaged, the smaller sliding wagon is locked to the practically stationary wagon, and cannot move in either direction. (See attached model)

Concept C

This concept is based on an angled pointer interacting on a toothed face. Once engaged, the angle of the pointer makes the freely sliding wagon able to move backwards into a new position, but not forward. (See attached model)

Concept D

This concept applies long teeth in the direction of the rails. An engagement slider is activated by a spring to create friction between the teeth to lock them. Once engaged, this friction locks the wagons and the freely sliding wagon cannot move in either direction. (See attached model)

Physical attributes

Interface Friction – This is an indicator of how much friction the mechanism provides in the interface. A higher rating indicates higher friction.

Holding force – This is an indicator of the holding force in the interface. A higher rating indicates more holding force.

Disengaging Force – This is an indicator of the required force to disengage the interface. A higher rating indicates more force.

Stability – How stable is the mechanism? A higher rating indicates a more stable mechanism.

Complexity – How many parts/features are present? A higher number indicates more complexity.

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Evaluation Matrix

Grade each of the concepts A, B, C and D on a scale from 0 to 10 according to the presence of each of the listed attributes.

Physical Attributes	Concept A	Concept B	Concept C	Concept D
Interface Friction				
Holding Force				
Disengaging Force				
Stability				
Complexity				

Influence of Physical Attributes

How will the presence of these attributes affect the technical problem? Please mark one alternative per attribute.

	Very Negative	Negative	Slightly Negative	Neutral	Slightly Positive	Positive	Very Positive
Interface Friction	☐	☐	☐	☐	☐	☐	☐
Holding Force	☐	☐	☐	☐	☐	☐	☐
Disengaging Force	☐	☐	☐	☐	☐	☐	☐
Stability	☐	☐	☐	☐	☐	☐	☐
Complexity	☐	☐	☐	☐	☐	☐	☐

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Pilot Experiment, Part II (20 min)

You have now finished your evaluation, and thereby part I of the experiment. In the second part, you are now asked to utilize your experience from this evaluation, and propose an improved solution to the technical problem.

In addition to the provided materials of part I, your provided materials for part II are:

- This description sheet
- Drawing equipment
- Blank A3-sheets of printer paper
- Four technical drawings of the technical system, without locking mechanisms.

Task Description

Your task in this part of the experiment is to design an optimum solution to the technical problem provided in part I, using the drawing equipment provided. Please feel free to use as many of the sheets of A3 paper, including the technical drawings already provided.

You will get 20 minutes for completing this task. Upon completion, you will be asked to hand in as many sheets of A3 paper describing your optimum solution as you prefer.

Thank you for your time and participation, and good luck.

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15.03.16
Deres dato

Vår referanse
JABE
Deres referanse

Background Information Questionnaire

This questionnaire is designed to collect additional background information about you.

Part A. Education

The questions in this section are designed to collect information on your education.

A1. What is your current level of achieved education?

- ☐ High School
- ☐ College
- ☐ Bachelor's Degree
- ☐ Master's Degree
- ☐ Ph.D.

A2. When did you graduate?

Month ☐☐ Year ☐☐☐☐

A3a. Please record your primary area of specialization.

Primary Area
of Specialization: ____

A3b. Please record any additional areas of specialization you currently have.

IF NONE: MARK THIS BOX: ☐

1. Area of Specialization: ____
2. Area of Specialization: ____
3. Area of Specialization: ____

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A4. Are you currently studying for a degree? If no, skip to part B. If yes, please specify:

- ☐ High School
- ☐ College
- ☐ Bachelor's Degree
- ☐ Master's Degree
- ☐ Ph.D.

A5. When do you plan to graduate?

Month ☐☐ Year ☐☐☐☐

A6a. Please record your primary area of specialization.

Primary Area
of Specialization: ____

A6b. Please record any additional areas of specialization you currently have.

IF NONE: MARK THIS BOX: ☐

1. Area of Specialization: ____________________________________
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3. Area of Specialization: ____________________________________

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Part B: Professional Experience

The questions in this section are designed to collect information on your career and whether and how they have changed over time. Please give estimates wherever suitable.

B1. For how long have you worked for a engineering company?

If you have never worked for any engineering companies: Skip to Part C.

Answer: ______________________________________

B2a. Where do you currently work?

If you have no current employer: Skip to B3

Company: ______________________________________

B2b. For how long have you worked for your current employer?

Answer: ______________________________________

B2c. Are you assigned to a specific department by your current employer?

☐ Management
☐ Research and Development (R&D)
☐ Testing and Verification
Other: ______________________________________

B3. For how long have you worked in the automotive industry?

If you have not worked in the automotive industry: Mark this box: ☐

Answer: ______________________________________

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Part C: Demographic Information

The questions in this section are designed to collect some of your demographic information.

C1. Are you:

☐ Male
☐ Female

C2. In what year were you born?

Year of Birth: ☐☐☐☐

C3. What is your nationality (i.e. citizenship)?
Please specify if you have multiple citizenships.

Answer: ____

Part D: Further Participation

D1. Are you willing to receive follow-up questions or surveys of this study via e-mail in the future? If yes, please write your e-mail address below.

E-mail address: ____

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Part E: General Information

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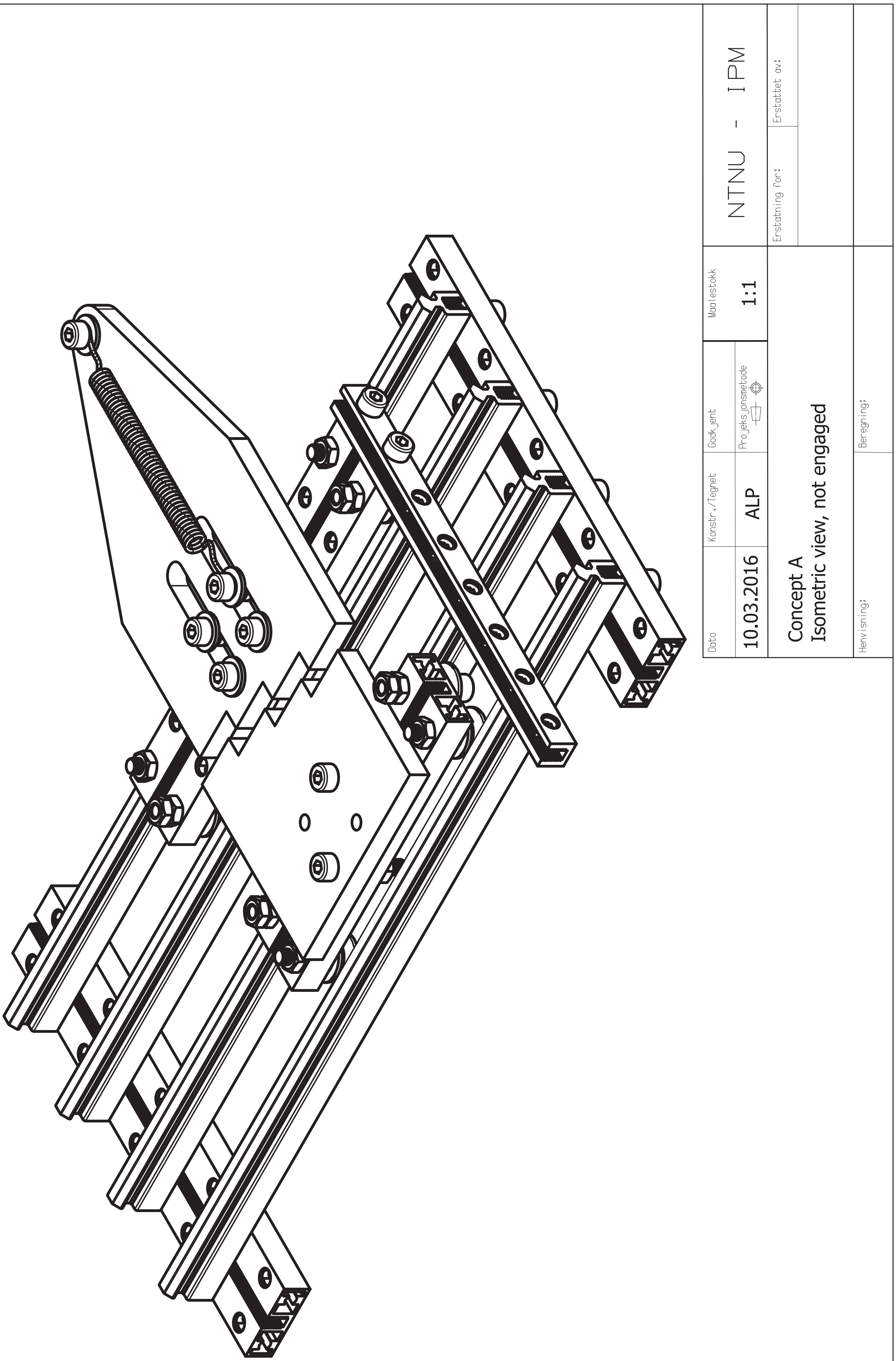

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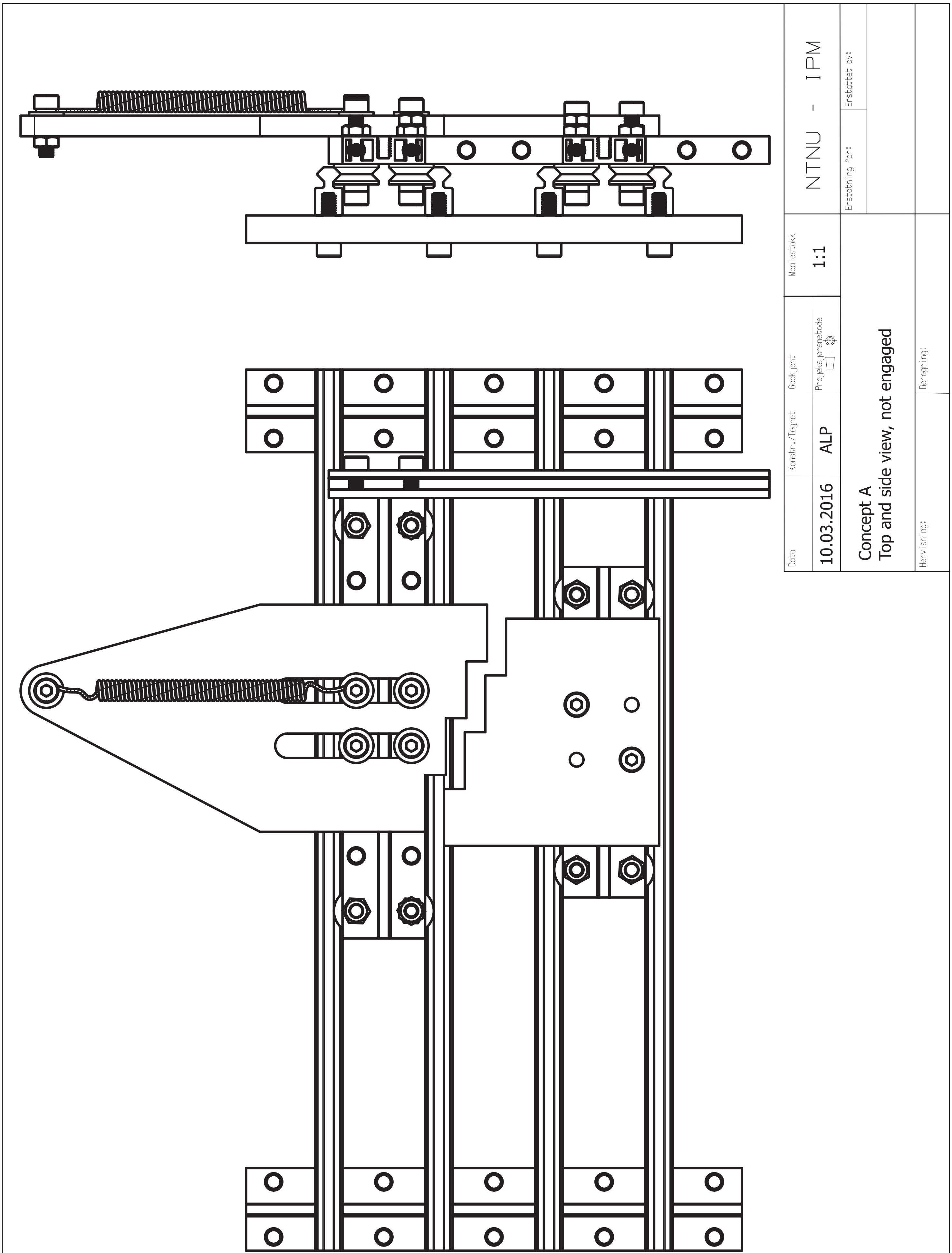

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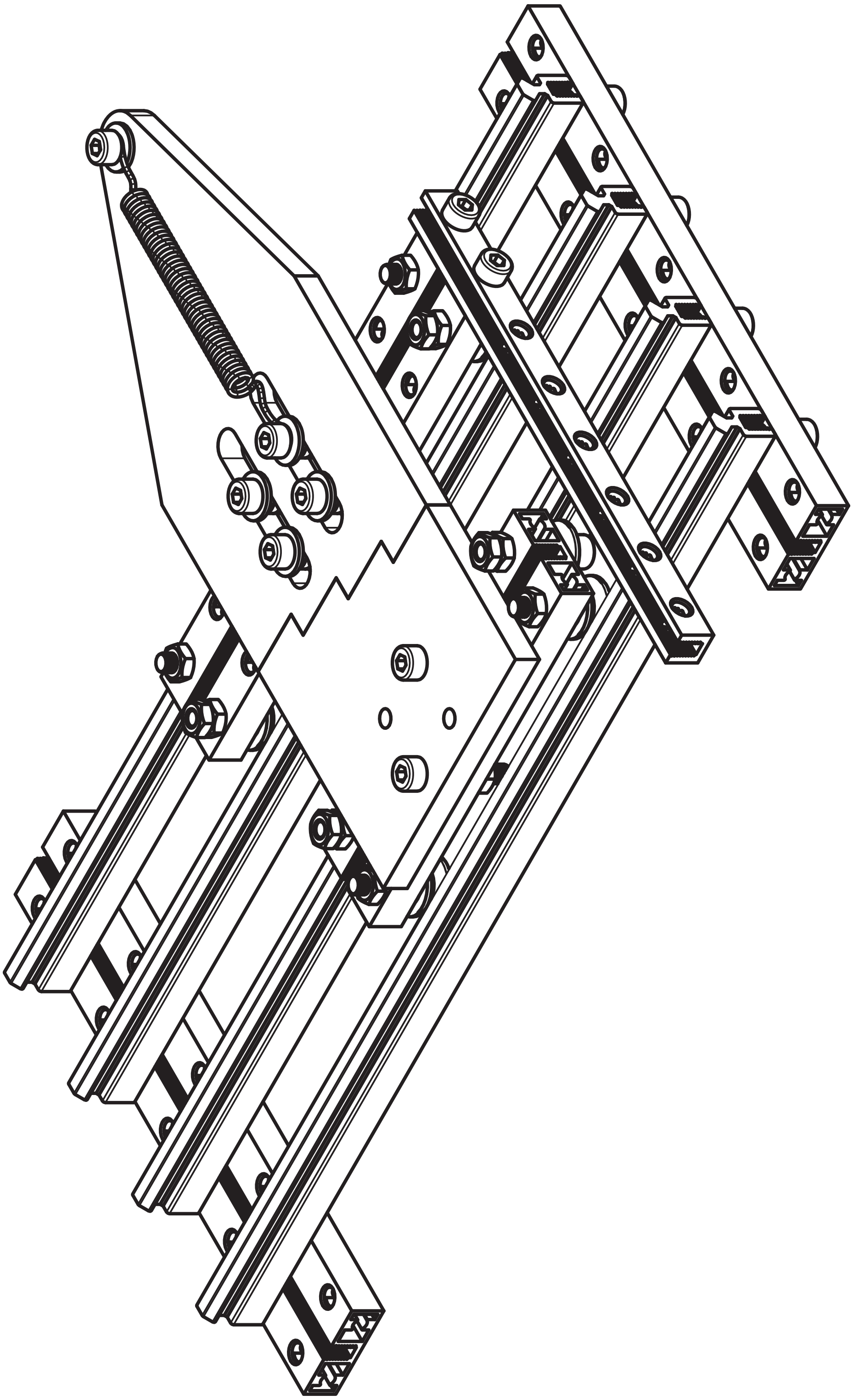

Dato	Konstr./Tegnet	Godkjent	Maalestokk
10.03.2016	ALP	Projeksjonsmetode	1:1

NTNU - IPM

Erstatning for:

Erstattet av:

Concept A
Isometric view, engaged

Henvisning:

Beregning:

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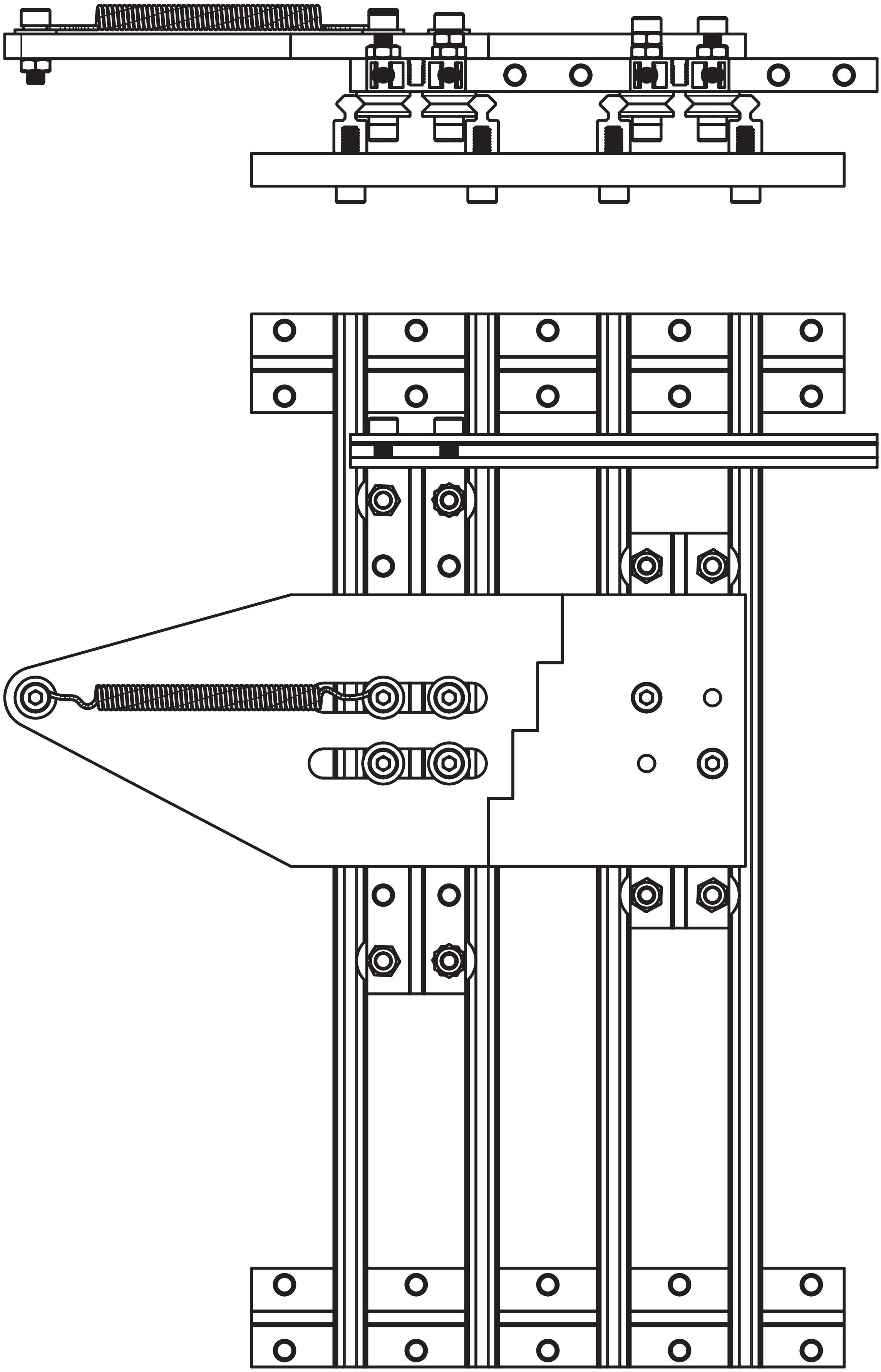


NTNU - IPM

Erstattet av:

Erstatning for:

Maalestokk: 1:1

Godkjent

Projeksjonsmetode

Konstr./Tegnet: ALP

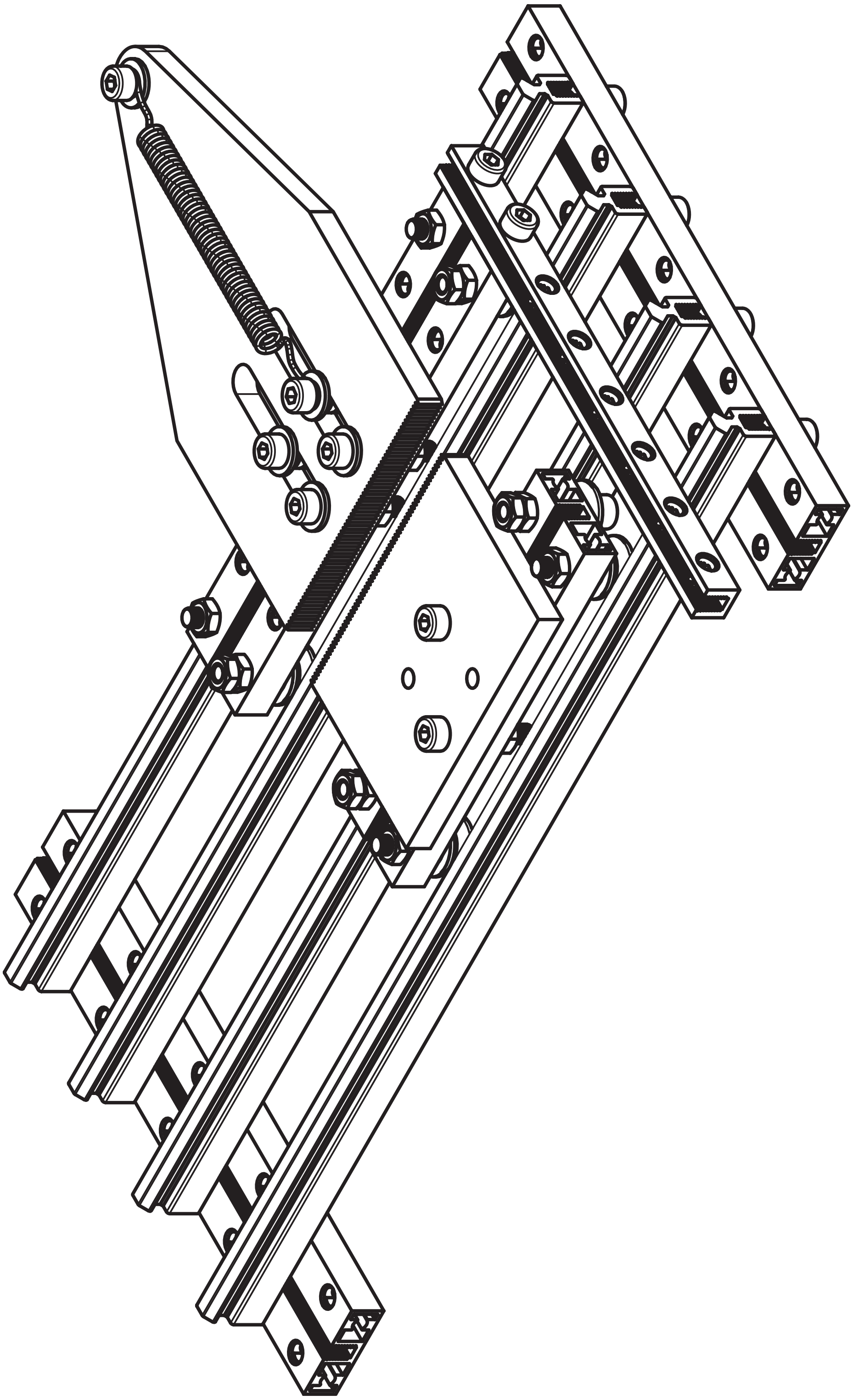
Dato: 10.03.2016

Concept A
Top and side view, engaged

Henvisning:

Beregning:

ORIGINAL DOCUMENT SIZE: A3



NTNU - IPM	
Maalestokk	1:1
Godkjent	Prosjeksjonsmetode
Konstr./Tegnet	ALP
Dato	10.03.2016

Concept B
Isometric view, not engaged

Henvisning:

Beregning:

Erstatning for:

Erstattet av:

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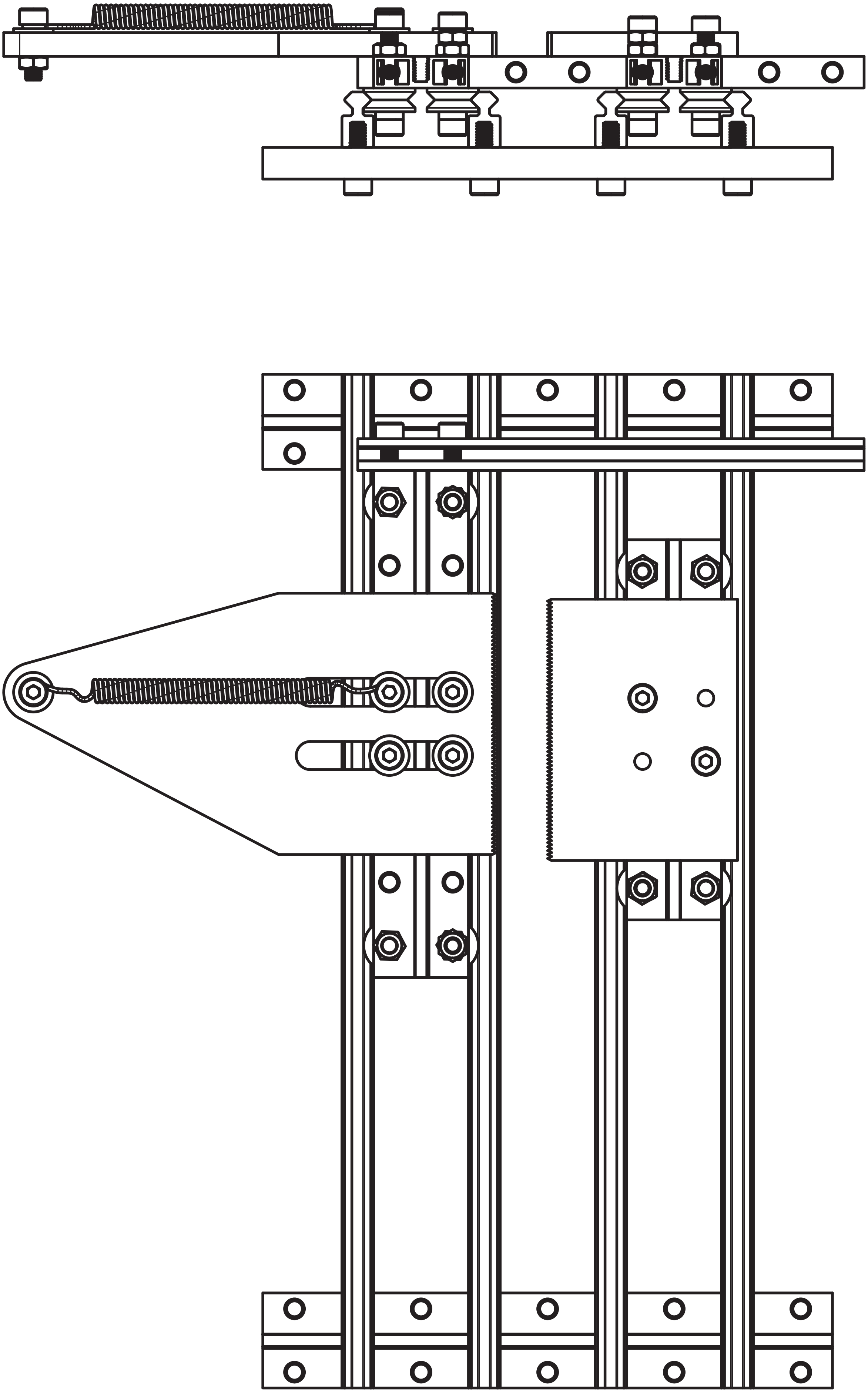

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Godkjent		Projeksjonsmetode
Maalestokk	1:1	
NTNU - IPM		
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Concept B Top and side view, not engaged		
Henvisning:	Beregning:	

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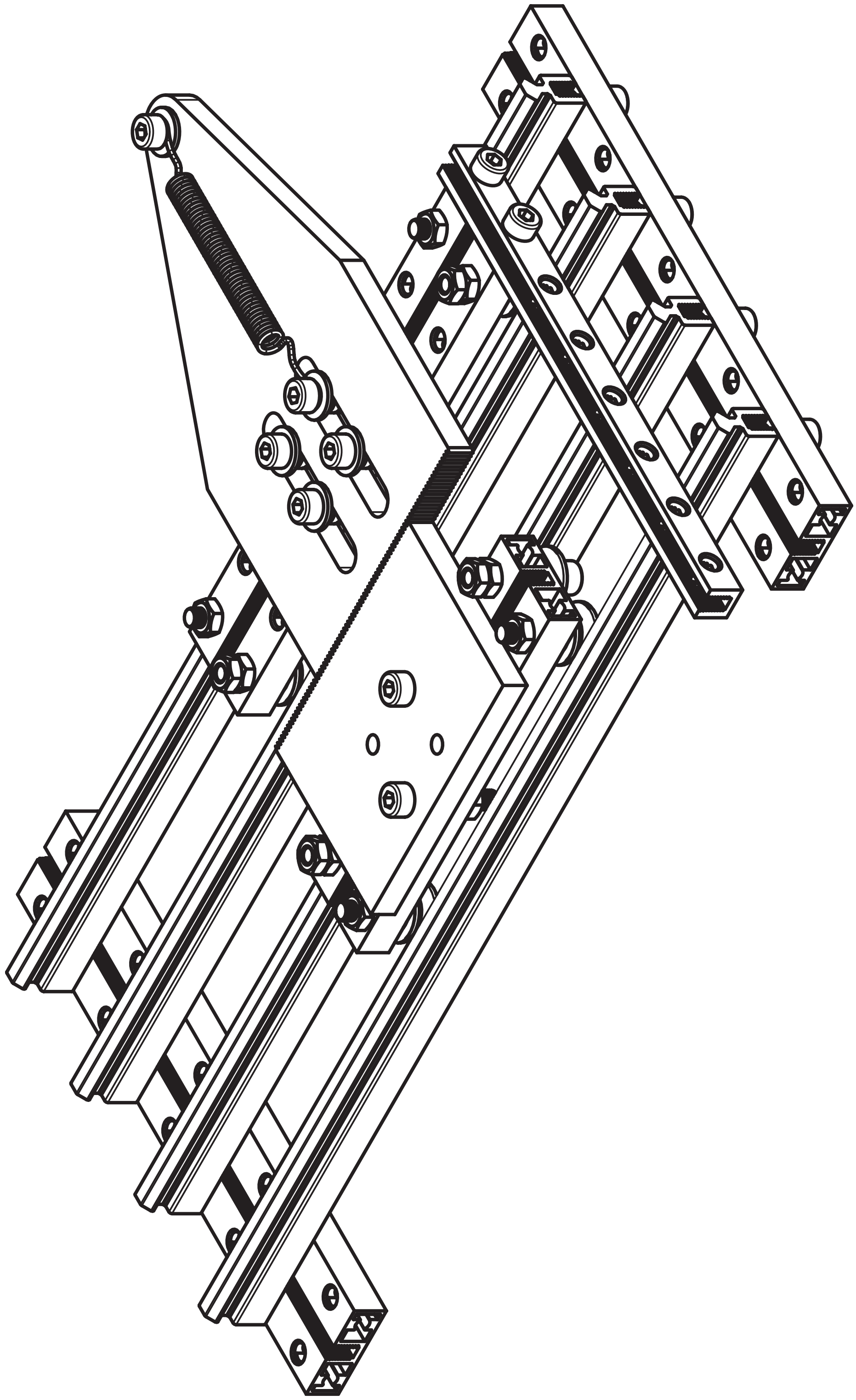

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Concept B
Isometric view, engaged

Henvisning:

Beregning:

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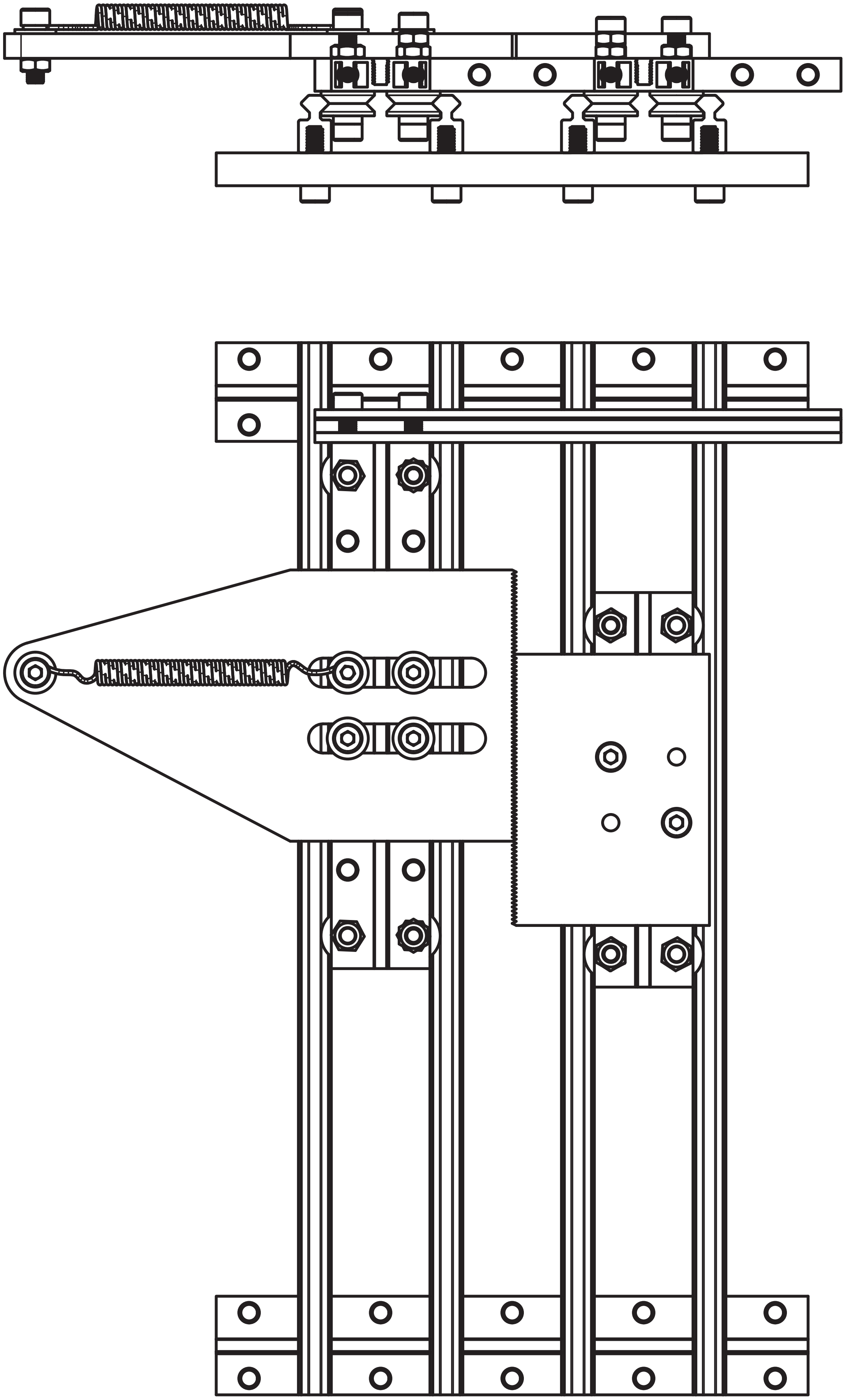

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Konstr./Tegnet	ALP
Godkjent	
Projeksjonsmetode	
Maalestokk	1:1
NTNU - IPM	
Erstatning for:	
Erstattet av:	
Concept B Top and side view, engaged	
Henvisning:	
Beregning:	

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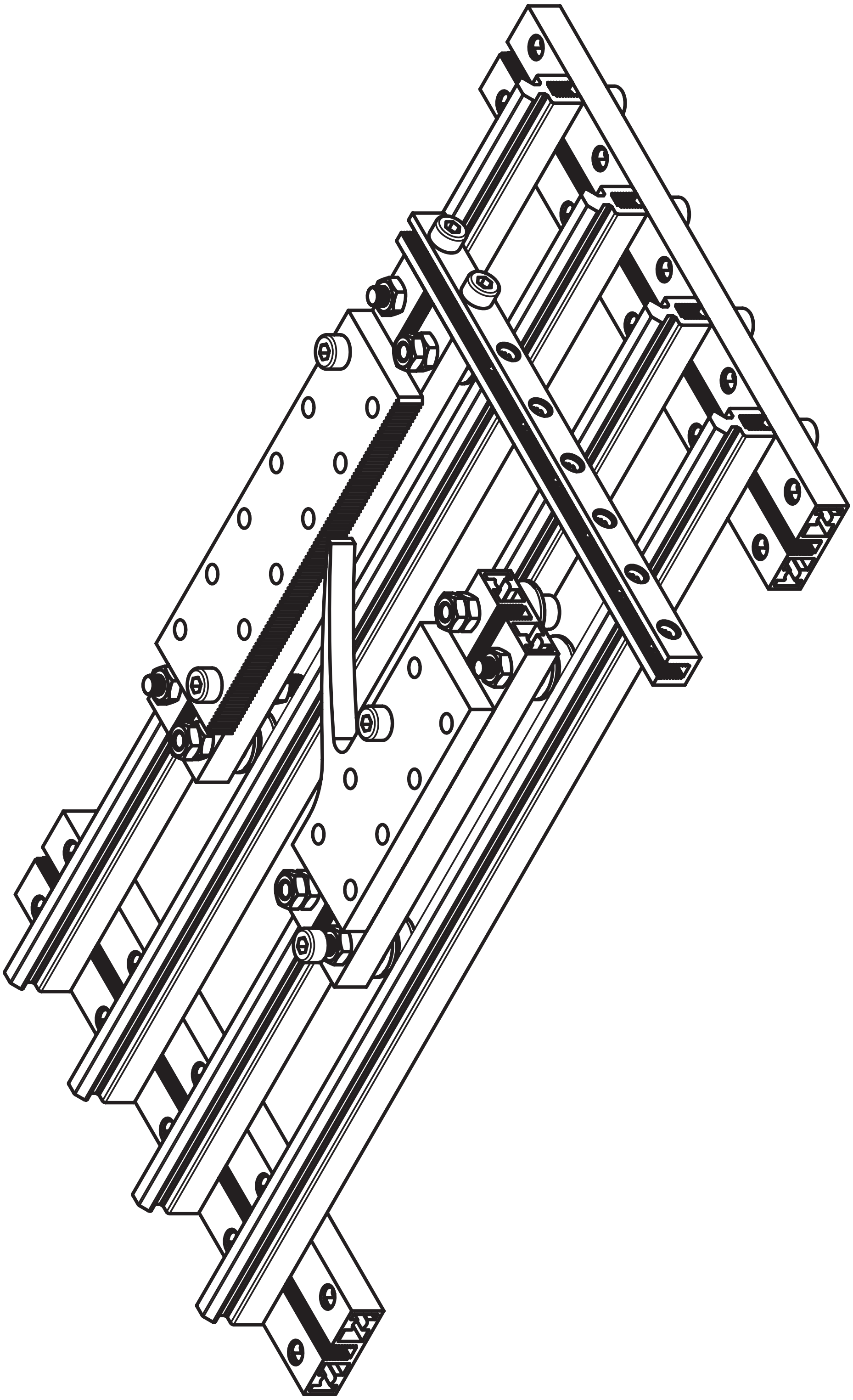

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10.03.2016	ALP	Projeksjonsmetode	1:1

NTNU - IPM

Erstatning for:

Erstattet av:

Concept C
Isometric view, not engaged

Henvisning:

Beregning:

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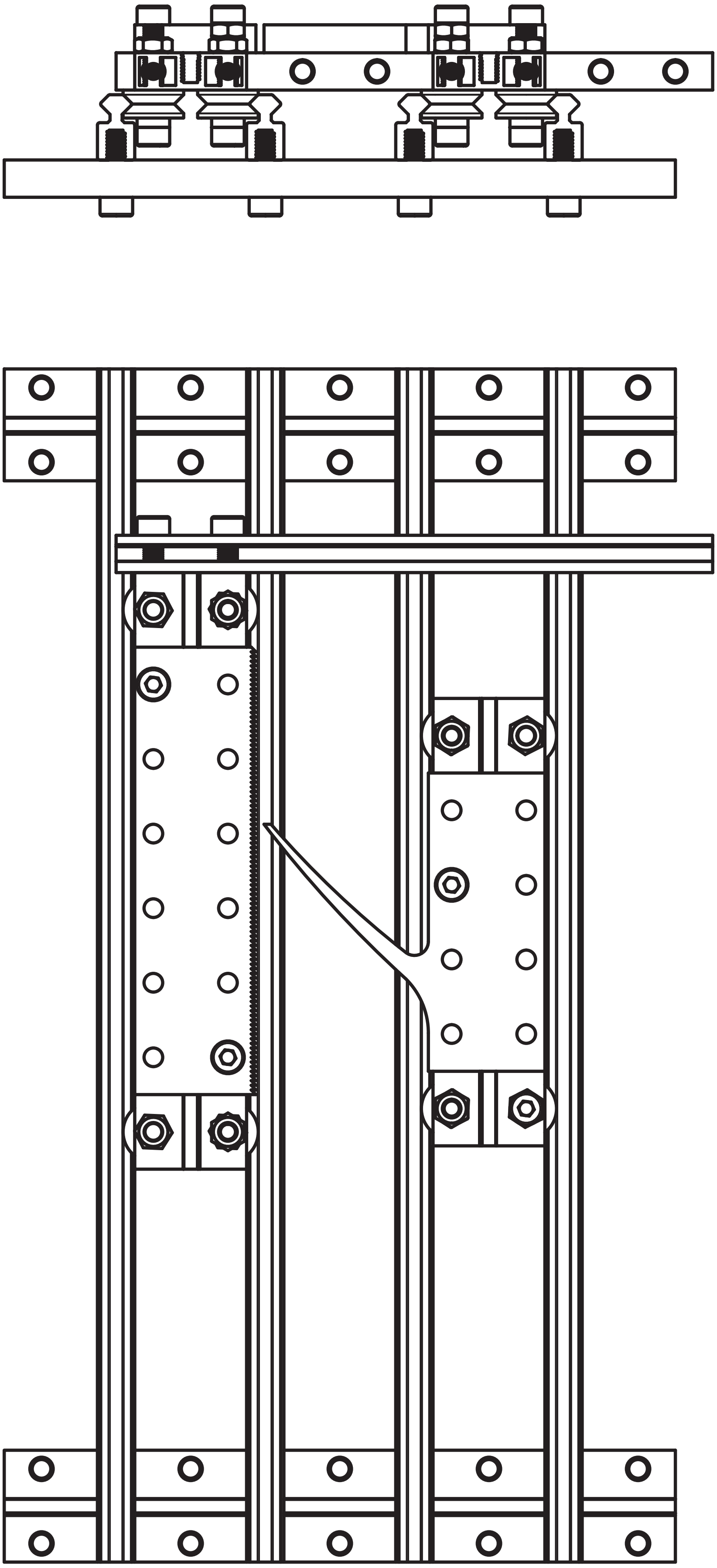

NTNU - IPM	
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Dato	10.03.2016
Konstr./Tegnet	ALP
Godkjent	
Projeksjonsmetode	
Henvisning:	
Beregning:	

Concept C
Top and side view, not engaged

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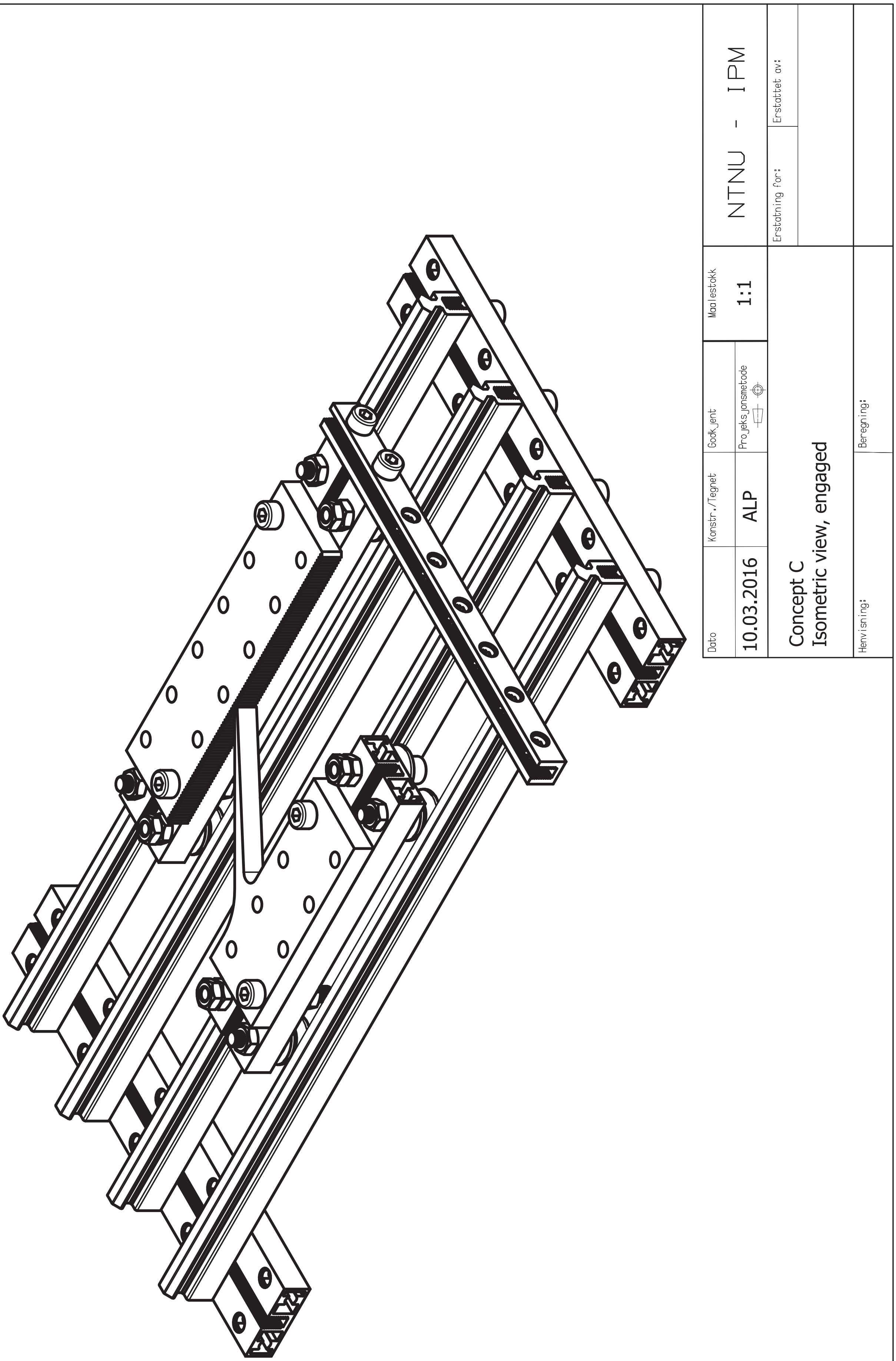

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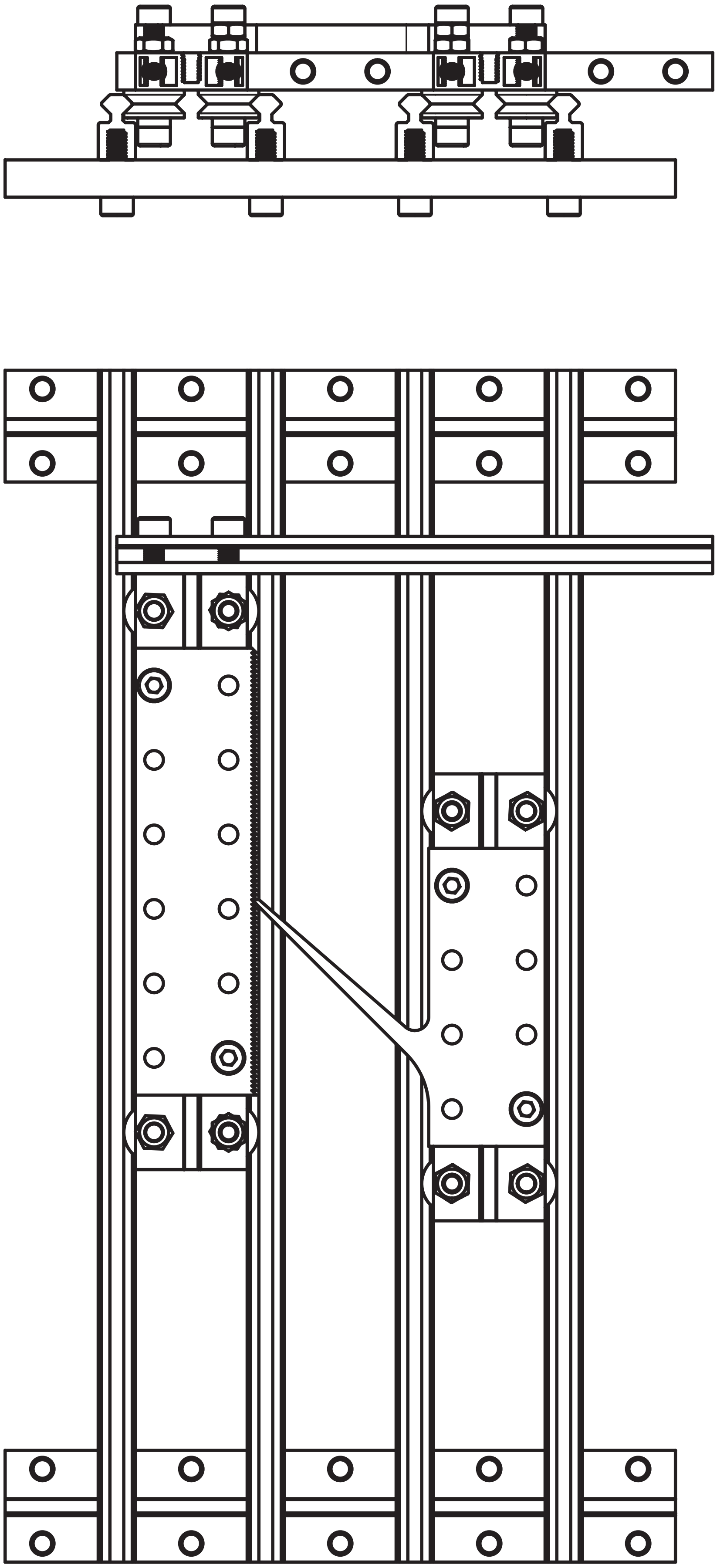

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Dato	Konstr./Tegnet	Godkjent	Maalestokk
10.03.2016	ALP	Projeksjonsmetode	1:1

Concept C
Top and side view, engaged

Erstatning for:

Erstattet av:

Henvisning:

Beregning:

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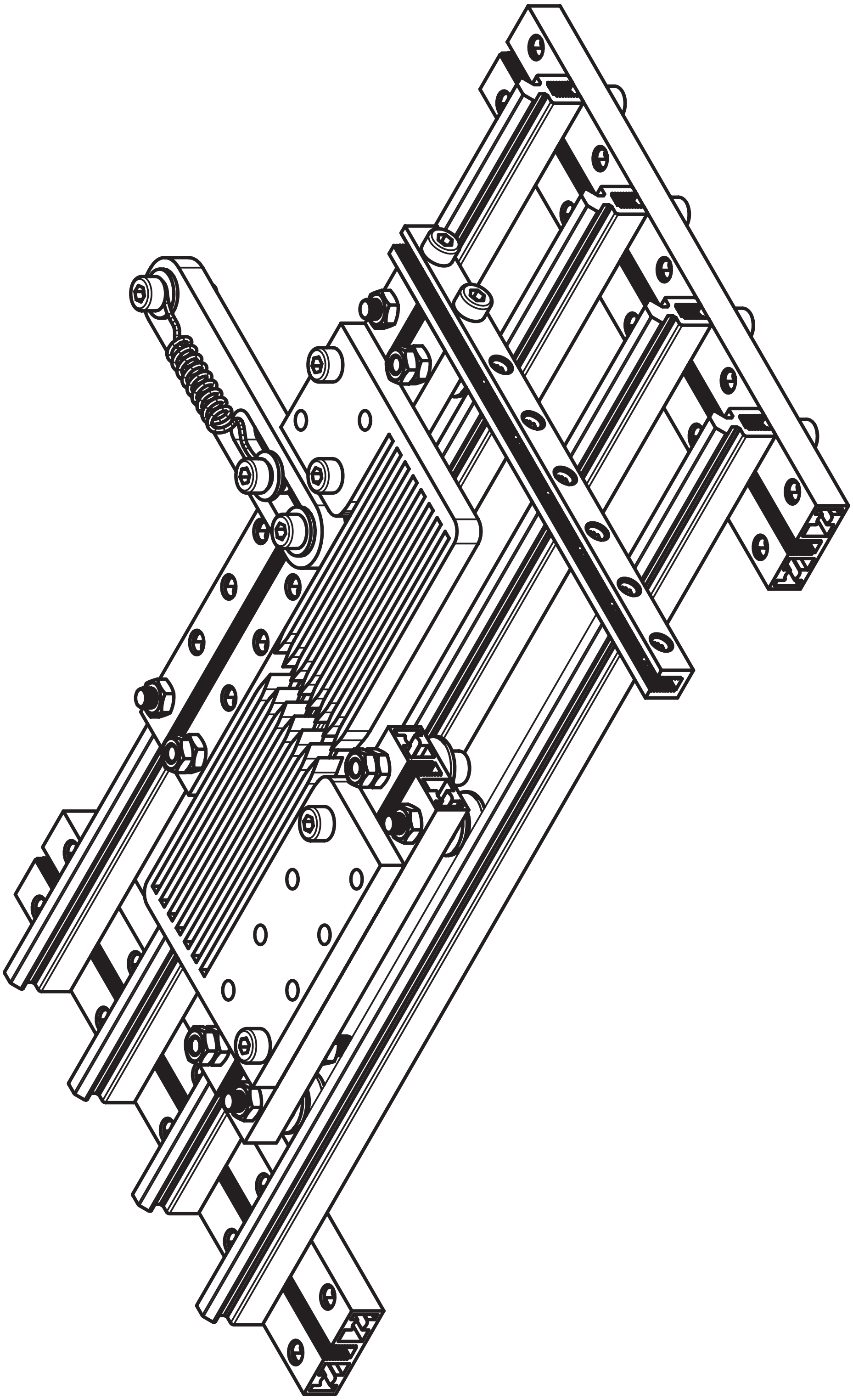

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Projeksjonsmetode			

Concept D
Isometric view, not engaged

NTNU - IPM

Erstatning for:

Erstattet av:

Henvisning:

Beregning:

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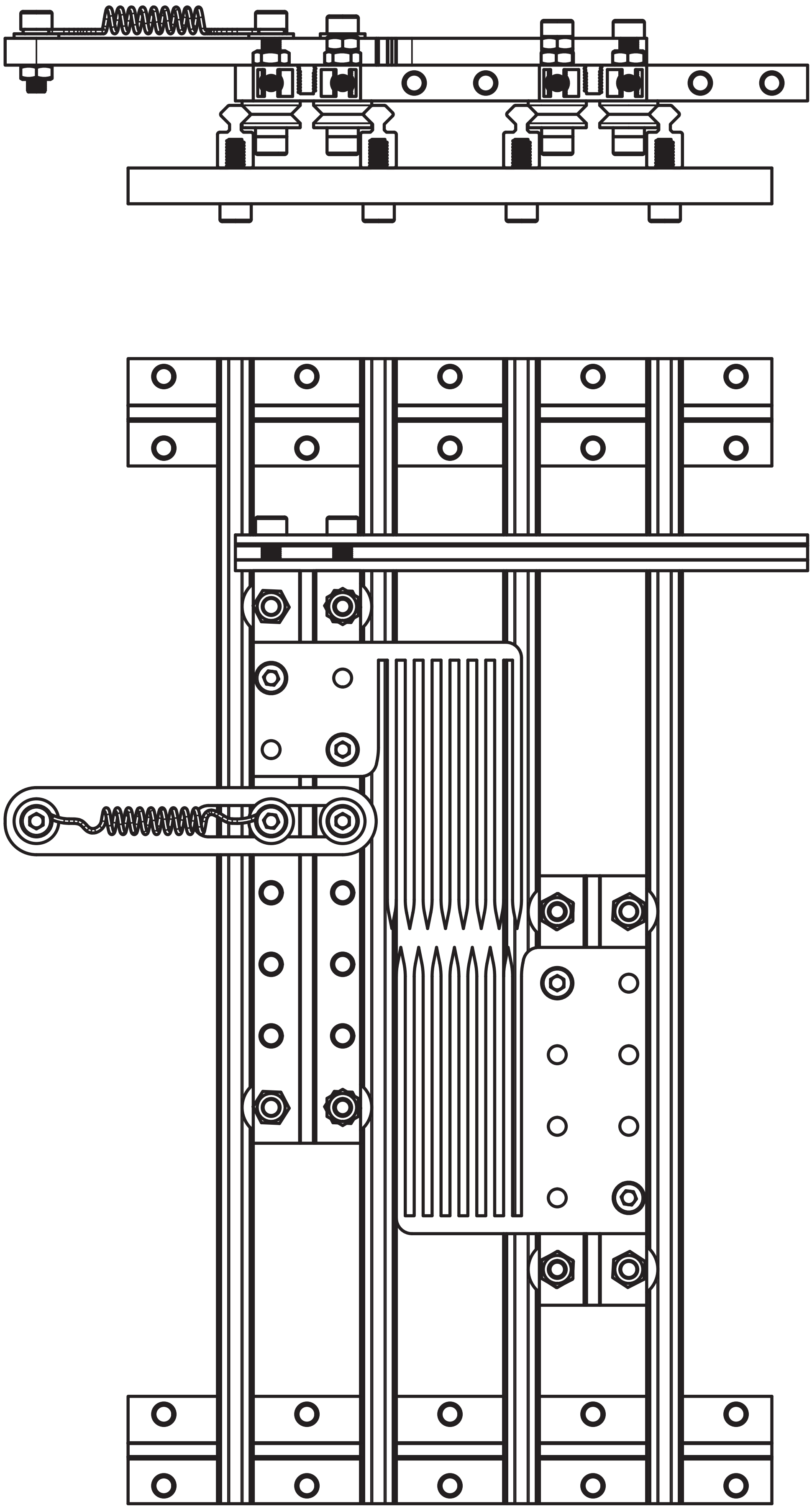

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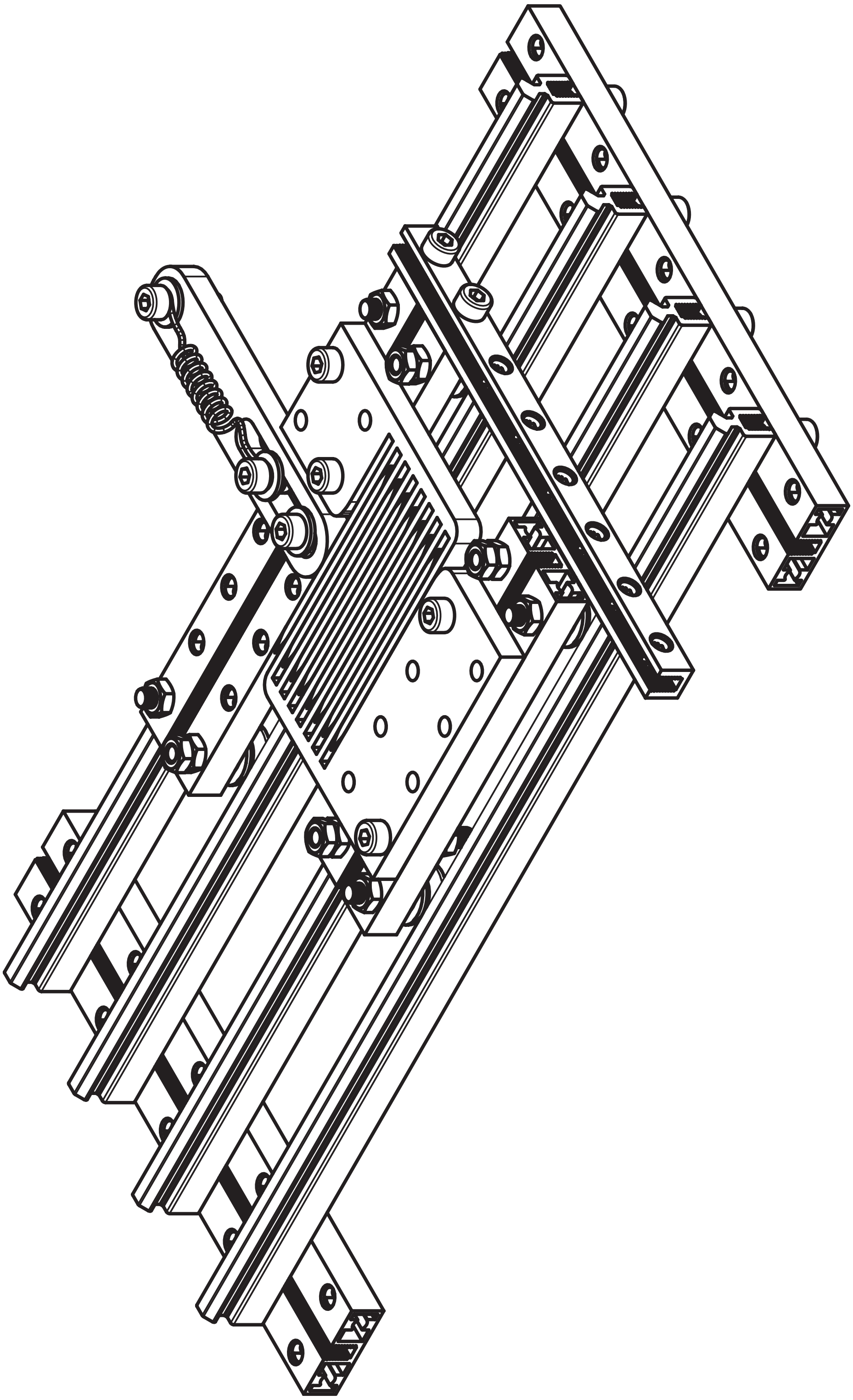
10.03.2016	ALP	Projeksjonsmetode	1:1	Erstatning for: / Erstattet av:

Concept D
Top and side view, not engaged

Henvisning:
Beregning:

ORIGINAL DOCUMENT SIZE: A3



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		Projeksjonsmetode	NTNU - IPM
Concept D Isometric view, engaged			Erstatning for:
			Erstattet av:
Henvisning:		Beregning:	

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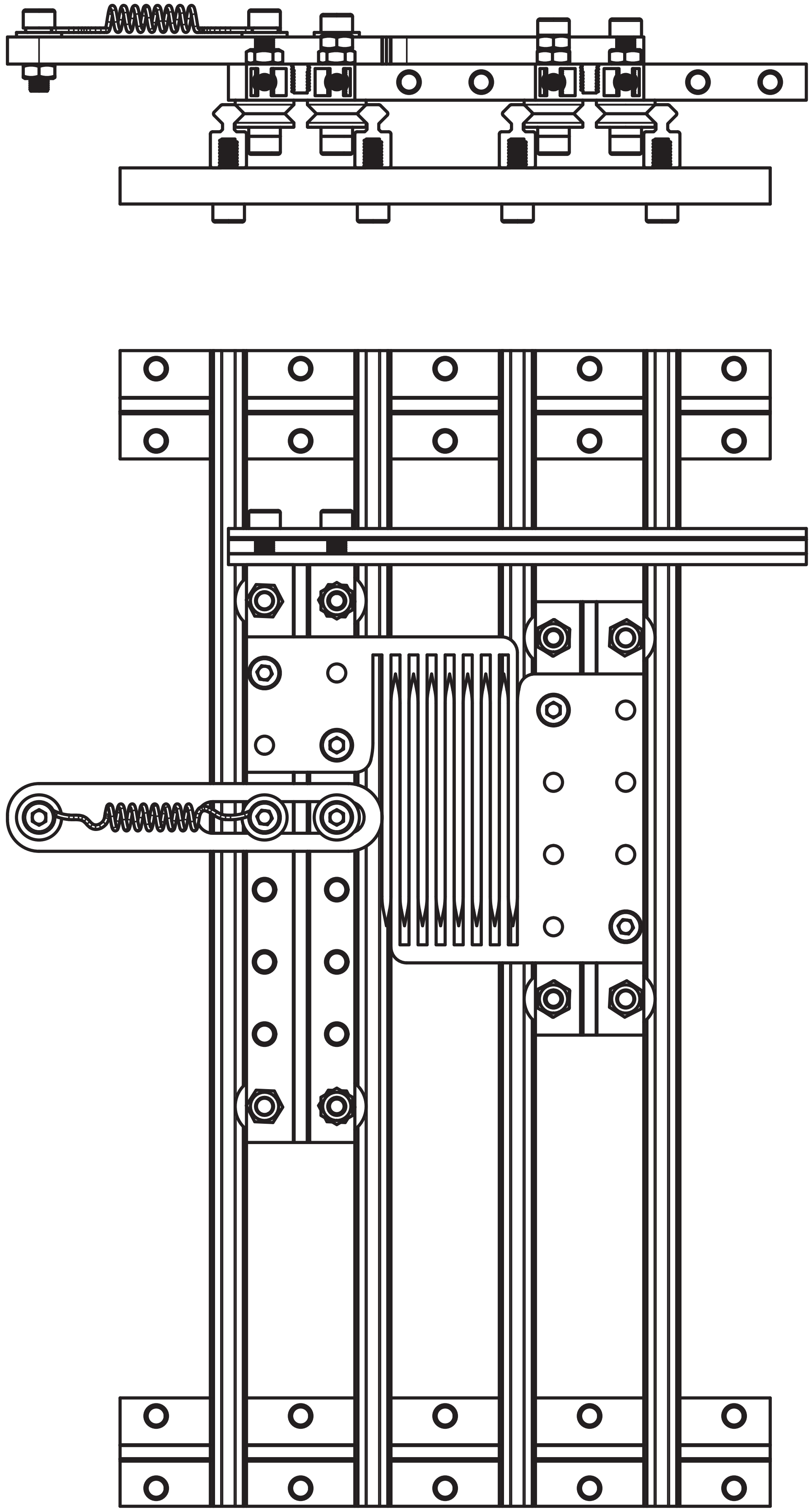


NTNU - IPM

Erstattet av:

Erstatning for:

Maalestokk: 1:1

Godkjent

Projeksjonsmetode

Konstr./Tegnet: ALP

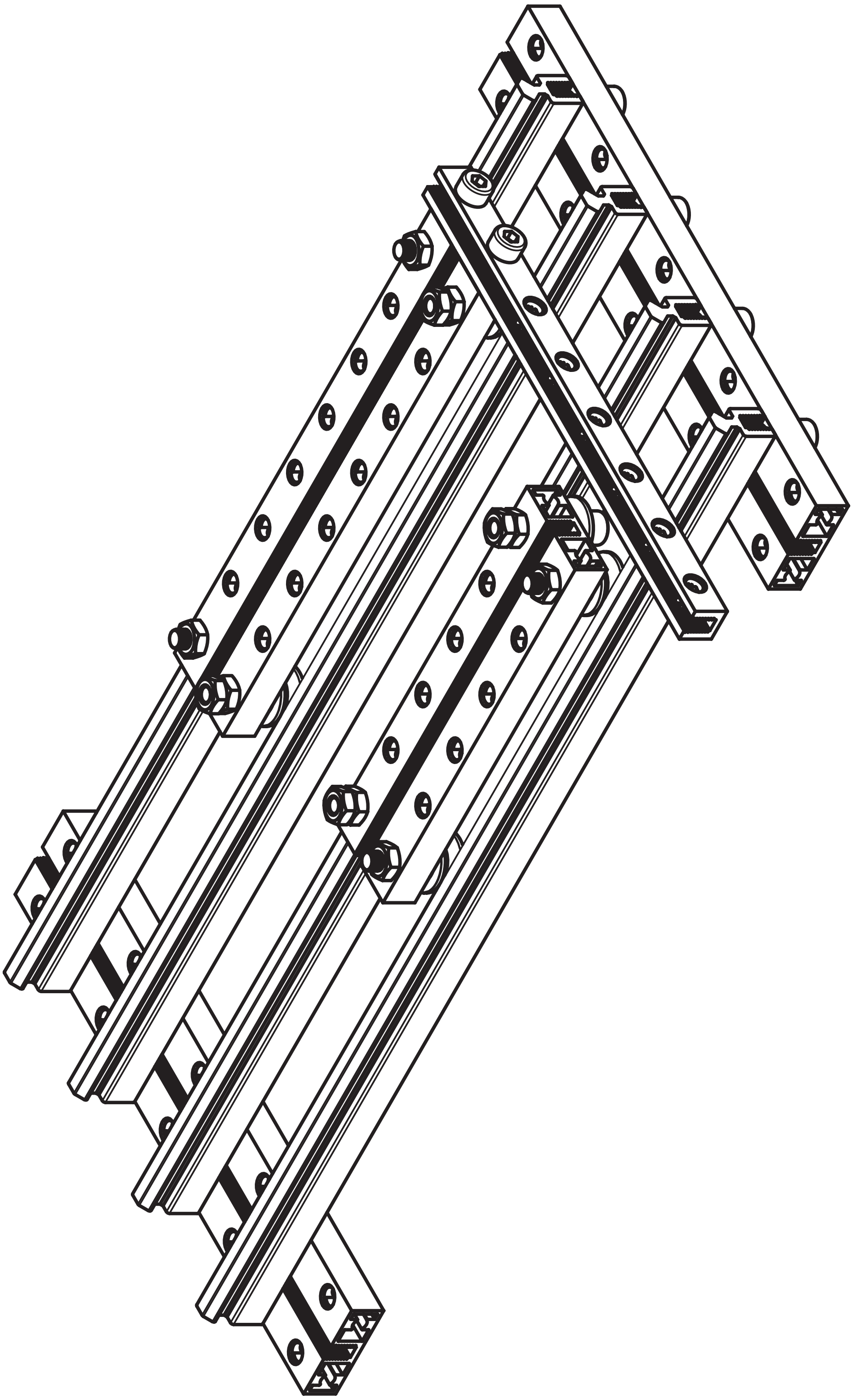
Dato: 10.03.2016

Concept D
Top and side view, engaged

Henvisning:

Beregning:

ORIGINAL DOCUMENT SIZE: A3



NTNU - IPM

Erstatning for:

Erstattet av:

Maalestokk: 1:1

Dato: 10.03.16

Konstr./Tegnet: JABE

Godkjent

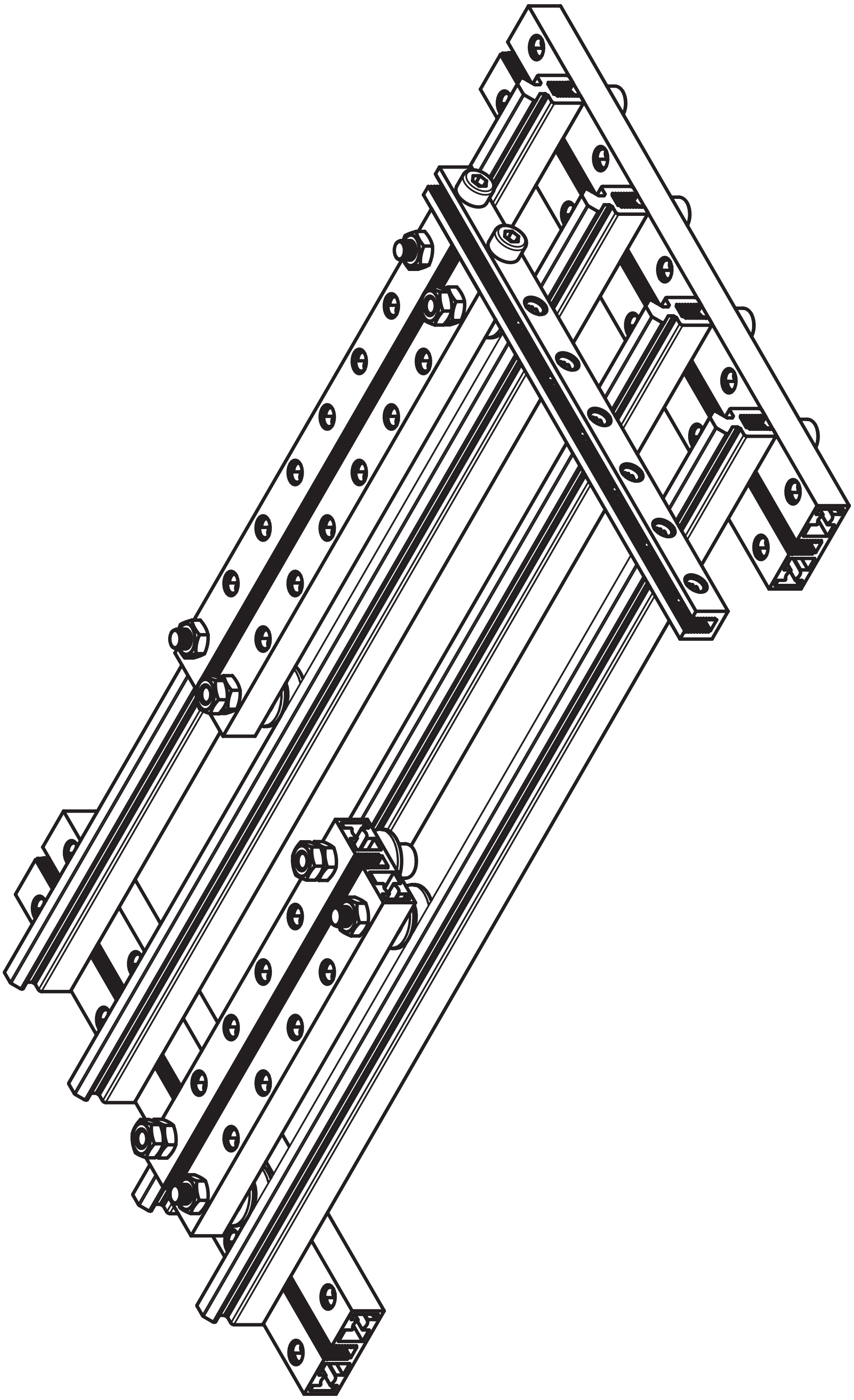
Projeksjonsmetode

Empty Concept Setup
Isometric View, Engaged

Henvisning:

Beregning:

ORIGINAL DOCUMENT SIZE: A3



Dato	Konstr./Tegnet	Godkjent	Projeksjonsmetode	Maalestokk	NTNU - IPM
10.03.16	JABE			1:1	

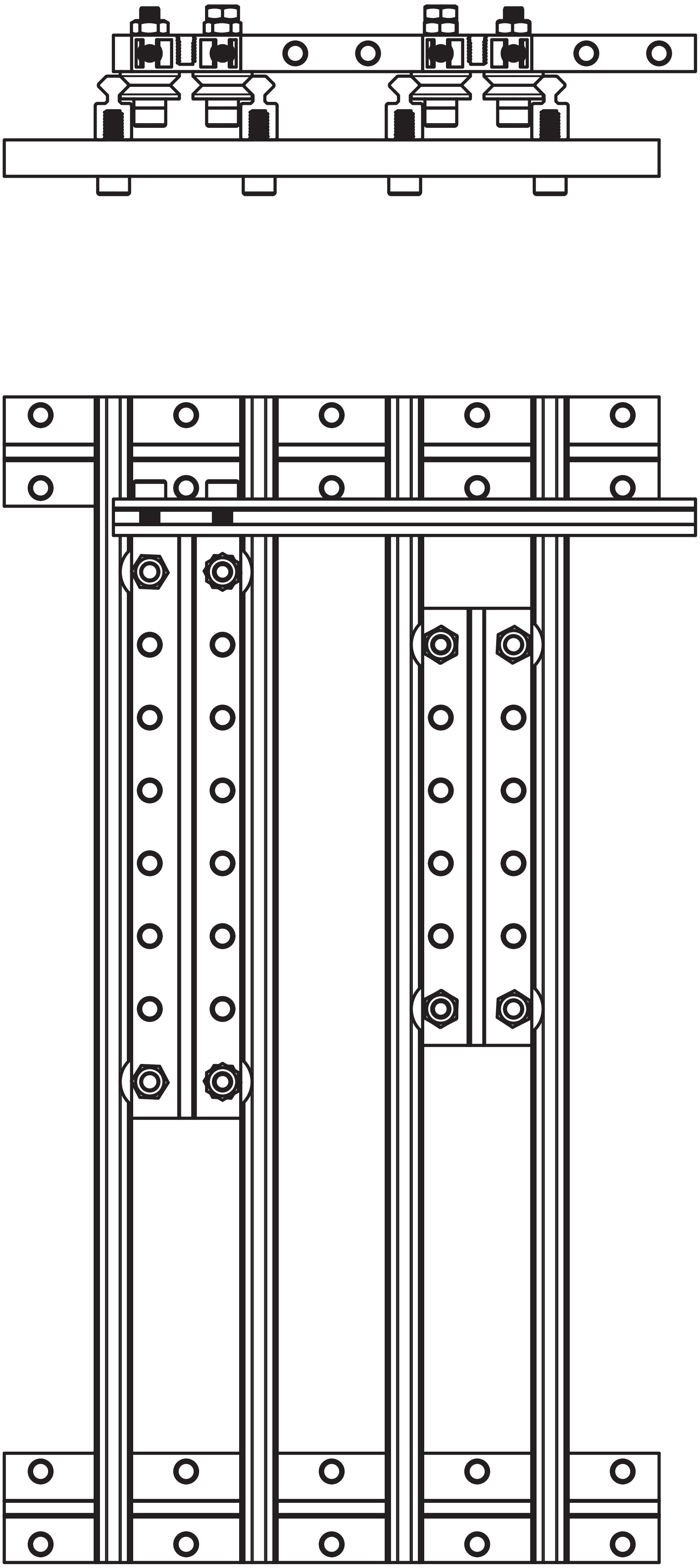
Empty Concept Setup
Isometric View, Not Engaged

Erstatning for:

Erstattet av:

Henvisning:

Beregning:



NTNU - IPM

Erstatning for:

Erstattet av:

Maalestokk: 1:1

Godkjent

Projeksjonsmetode

Konstr./Tegnet: JABE

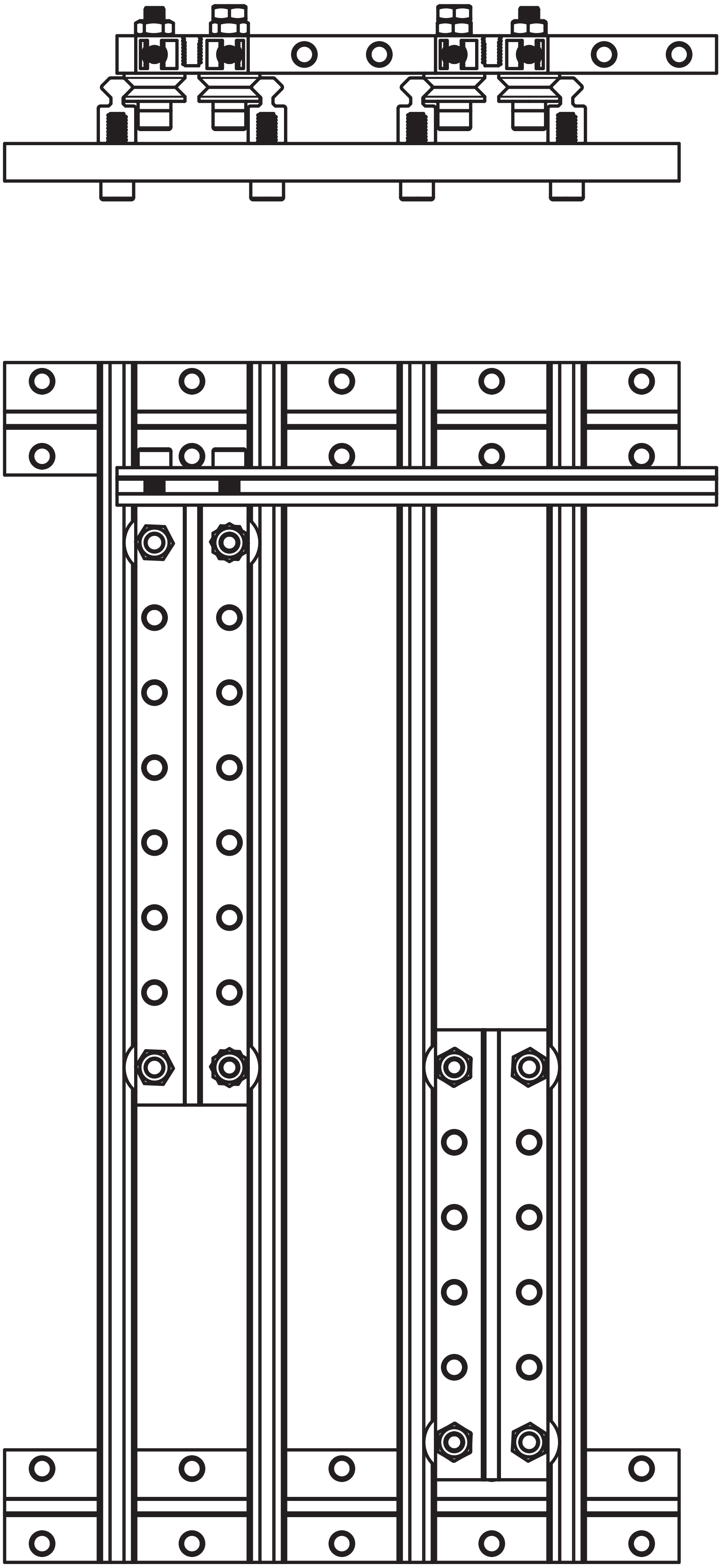
Dato: 10.03.16

Empty Concept Setup
Top and Side View, Engaged

Henvisning:

Beregning:

ORIGINAL DOCUMENT SIZE: A3



NTNU - IPM

Erstatning for:

Erstattet av:

Maalestokk: 1:1

Dato: 10.03.16

Konstr./Tegnet: JABE

Godkjent:

Projeksjonsmetode

Empty Concept Setup
Top and Side View, Not Engaged

Henvisning:

Beregning:

ORIGINAL DOCUMENT SIZE: A3

Appendix B

Expert Evaluation Walkthrough

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Expert Evaluation Walkthrough

In this appendix, we provide a walkthrough of the expert evaluation that is shown in Chapter 3. This is done to increase repeatability of the experiment. The attributes that are listed here are the same as the ones described in Appendix A, and are defined as follows;

Interface Friction	This is an indicator of how much friction the mechanism provides in the interface. A higher rating indicates higher friction.
Holding force	This is an indicator of the holding force in the interface. A higher rating indicates more holding force.
Disengaging Force	This is an indicator of the required force to disengage the interface. A higher rating indicates more force.
Stability	How stable is the mechanism? A higher rating indicates a more stable mechanism.
Complexity	How many parts/features are present? A higher number indicates more complexity.

Evaluation of the Pre-Defined Concepts

As stated in Appendix A, participants are asked to rate the *presence* of each attribute. Some of the attributes may be somewhat overlapping, and will arguably have some room for interpretation (e.g. The holding force of Concept D may depend heavily on friction, giving it a high ‘Interface Friction’ score, but as the holding force may be less present than in the other concepts, the ‘Holding Force’ score is relatively low). Through our work with the concepts with Kongsberg Automotive, abstracting them, creating CAD models and drawings, we have gained extensive insight into their functionality, and this experience is what we based the expert evaluation upon. We have set the following criteria for our evaluation:

Interface Friction	To what degree does the concept depend on friction force to stay engaged?
Holding force	This is the force that can be transferred from one wagon to the other, through compression. To what degree is the concept able to resist separation once engaged?

Disengaging Force	This can be interpreted as the force required to disengage the mechanism either a) when it is under load or b) when it is not.
Stability	How stable is the mechanism? A higher rating indicates a more stable mechanism.
Complexity	How many parts/features are present? A higher number indicates more complexity.

This resulted in the following expert evaluation of the pre-defined concepts:

	Very Negative	Negative	Slightly Negative	Neutral	Slightly Positive	Positive	Very Positive
Interface Friction	☐	☐	☑	☐	☐	☐	☐
Holding Force	☐	☐	☐	☐	☐	☐	☑
Disengaging Force	☑	☐	☐	☐	☐	☐	☐
Stability	☐	☐	☐	☐	☐	☐	☑
Complexity	☐	☑	☐	☐	☐	☐	☐

Physical Attributes	Concept A	Concept B	Concept C	Concept D
Interface Friction	0	6	4	10
Holding Force	10	7	6	3
Disengaging Force	5	3	7	1
Stability	8	6	3	3
Complexity	4	2	6	8

Fixation criteria

For the design fixation hypothesis we identified 11 features present in the pre-defined concepts, and assessed each of the participants’ designs from the iterative design round by how many of the features were present, adding up to a design fixation score. In the cases where a participant delivered more than one concept, their score is the average of the scores given their designs. We have included these evaluation features in this appendix, without further description. The design features used to evaluate design fixation are as follows:

- One-way mechanism
- Large steps
- Small teeth
- Uniform interface
- 45 degree asymmetric teeth
- 45 degree symmetric teeth
- Rod interface
- Friction fingers
- Side load

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Appendix C

SPSS Statistical Output

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APPENDIX C: Statistics

1 Weightings

1.1 Descriptive statistics

Affordance Level				Statistic	Std. Error
Weighting of Interface Friction	Low Affordance	Mean		,50	,398
		95% Confidence Interval for Mean	Lower Bound	-,35	
			Upper Bound	1,35	
		5% Trimmed Mean		,50	
		Median		,50	
		Variance		2,533	
		Std. Deviation		1,592	
		Minimum		-2	
		Maximum		3	
		Range		5	
		Interquartile Range		3	
		Skewness		-,170	,564
		Kurtosis		-1,256	1,091
	High Affordance	Mean		,12	,477
		95% Confidence Interval for Mean	Lower Bound	-,89	
			Upper Bound	1,13	
		5% Trimmed Mean		,08	
		Median		0,00	
		Variance		3,860	
		Std. Deviation		1,965	
		Minimum		-2	
		Maximum		3	
		Range		5	
		Interquartile Range		4	
		Skewness		,151	,550
		Kurtosis		-1,743	1,063
Weighting of Holding Force	Low Affordance	Mean		1,94	,392
		95% Confidence Interval for Mean	Lower Bound	1,10	
			Upper Bound	2,77	
		5% Trimmed Mean		2,15	
		Median		2,00	
		Variance		2,463	
		Std. Deviation		1,569	
		Minimum		-3	
		Maximum		3	
		Range		6	

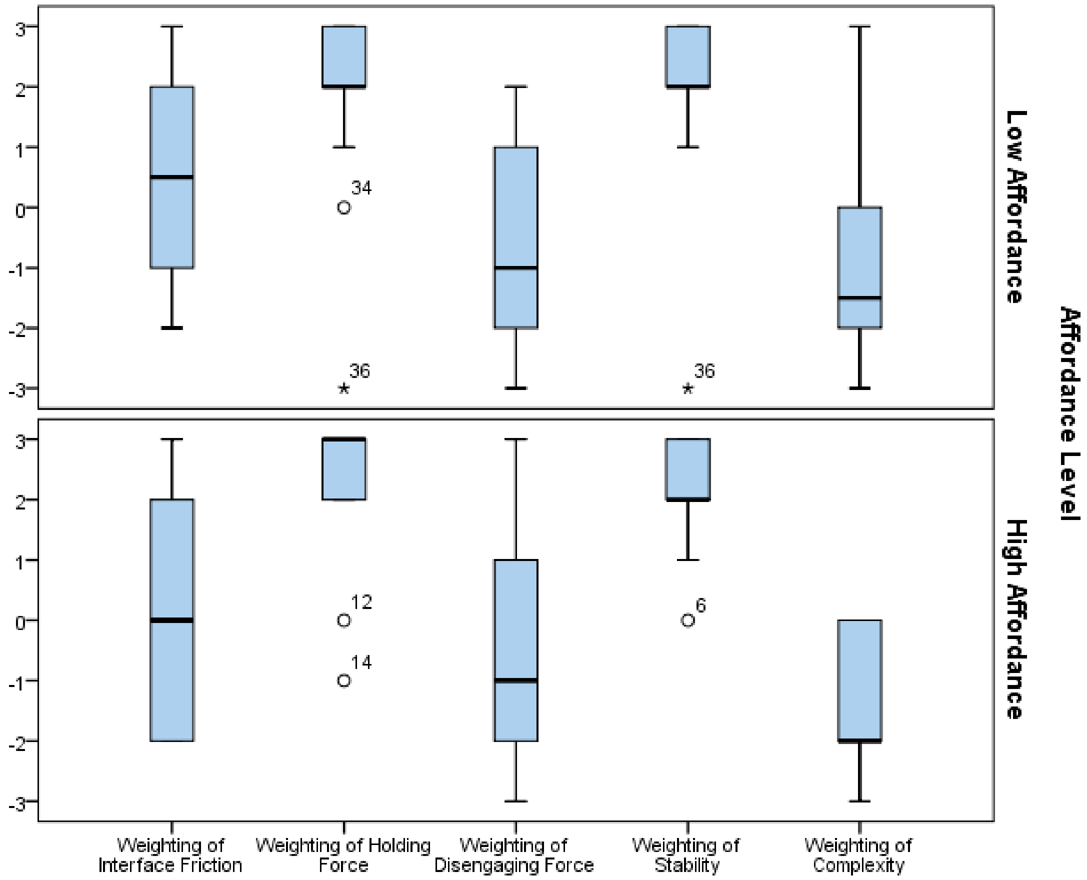
		Interquartile Range		1	
		Skewness		-2,367	,564
		Kurtosis		6,447	1,091
	High Affordance	Mean		2,24	,278
		95% Confidence Interval for Mean	Lower Bound	1,65	
			Upper Bound	2,83	
		5% Trimmed Mean		2,37	
		Median		3,00	
		Variance		1,316	
		Std. Deviation		1,147	
		Minimum		-1	
		Maximum		3	
		Range		4	
		Interquartile Range		1	
		Skewness		-1,927	,550
		Kurtosis		3,578	1,063
Weighting of Disengaging Force	Low Affordance	Mean		-,50	,447
		95% Confidence Interval for Mean	Lower Bound	-1,45	
			Upper Bound	,45	
		5% Trimmed Mean		-,50	
		Median		-1,00	
		Variance		3,200	
		Std. Deviation		1,789	
		Minimum		-3	
		Maximum		2	
		Range		5	
		Interquartile Range		3	
		Skewness		,160	,564
		Kurtosis		-1,461	1,091
	High Affordance	Mean		-,76	,433
		95% Confidence Interval for Mean	Lower Bound	-1,68	
			Upper Bound	,15	
		5% Trimmed Mean		-,85	
		Median		-1,00	
		Variance		3,191	
		Std. Deviation		1,786	
		Minimum		-3	
		Maximum		3	
		Range		6	
		Interquartile Range		3	
		Skewness		,717	,550
		Kurtosis		-,503	1,063
Weighting of	Low Affordance	Mean		2,06	,370
		95% Confidence Interval for Mean	Lower Bound	1,27	
			Upper Bound	2,85	

				Statistic	Std. Error
		5% Trimmed Mean		2,29	
		Median		2,00	
		Variance		2,196	
		Std. Deviation		1,482	
		Minimum		-3	
		Maximum		3	
		Range		6	
		Interquartile Range		1	
		Skewness		-2,931	,564
		Kurtosis		10,002	1,091
	High Affordance	Mean		2,24	,202
		95% Confidence Interval for Mean	Lower Bound	1,81	
			Upper Bound	2,66	
		5% Trimmed Mean		2,32	
		Median		2,00	
		Variance		,691	
		Std. Deviation		,831	
		Minimum		0	
		Maximum		3	
		Range		3	
		Interquartile Range		1	
		Skewness		-1,236	,550
		Kurtosis		2,007	1,063
Weighting of Complexity	Low Affordance	Mean		-1,00	,418
		95% Confidence Interval for Mean	Lower Bound	-1,89	
			Upper Bound	-,11	
		5% Trimmed Mean		-1,11	
		Median		-1,50	
		Variance		2,800	
		Std. Deviation		1,673	
		Minimum		-3	
		Maximum		3	
		Range		6	
		Interquartile Range		2	
		Skewness		1,171	,564
		Kurtosis		1,095	1,091
	High Affordance	Mean		-1,29	,268
		95% Confidence Interval for Mean	Lower Bound	-1,86	
			Upper Bound	-,73	
		5% Trimmed Mean		-1,27	
		Median		-2,00	
		Variance		1,221	
		Std. Deviation		1,105	

	Minimum	-3	
	Maximum	0	
	Range	3	
	Interquartile Range	2	
	Skewness	,035	,550
	Kurtosis	-1,486	1,063

1.2 Determining outliers

We produce boxplot for the distribution, to examine outliers.



Outliers found:

- Holding Force; Participant 34, 36, 12 and 14
- Stability; Participant 36 and 6

1.3 Normality Test (Shapiro-Wilk)

Affordance Level		Kolmogorov-Smirnov[a] Statistic	df	Sig.	Shapiro-Wilk Statistic	df	Sig.
Weighting of Interface Friction	Low Affordance	,202	16	,080	,915	16	,140
	High Affordance	,212	17	,040	,840	17	,008
Weighting of Holding Force	Low Affordance	,328	16	,000	,683	16	,000
	High Affordance	,301	17	,000	,684	17	,000
Weighting of Disengaging Force	Low Affordance	,174	16	,200*	,896	16	,070
	High Affordance	,226	17	,021	,896	17	,058
Weighting of Stability	Low Affordance	,358	16	,000	,599	16	,000
	High Affordance	,271	17	,002	,778	17	,001
Weighting of Complexity	Low Affordance	,225	16	,030	,869	16	,026
	High Affordance	,268	17	,002	,825	17	,005

Non-Normailties:

- Interface Friction; HA
- Holding Force; LA + HA
- Stability; LA + HA
- Complexity; LA + HA

1.4 Student T-Test

Affordance Level		N	Mean	Std. Deviation	Std. Error Mean
Weighting of Interface Friction	Low Affordance	16	,50	1,592	,398
	High Affordance	17	,12	1,965	,477
Weighting of Holding Force	Low Affordance	16	1,94	1,569	,392
	High Affordance	17	2,24	1,147	,278
Weighting of Disengaging Force	Low Affordance	16	-,50	1,789	,447
	High Affordance	17	-,76	1,786	,433
Weighting of Stability	Low Affordance	16	2,06	1,482	,370
	High Affordance	17	2,24	,831	,202
Weighting of Complexity	Low Affordance	16	-1,00	1,673	,418
	High Affordance	17	-1,29	1,105	,268

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Weighting of Interface Friction	Equal variances assumed	2,488	,125	,612	31	,545	,382	,625	-,892	1,657
	Equal variances not assumed			,616	30,351	,543	,382	,621	-,885	1,650
Weighting of Holding Force	Equal variances assumed	,225	,638	-,625	31	,537	-,298	,476	-1,269	,674
	Equal variances not assumed			-,619	27,389	,541	-,298	,481	-1,284	,688
Weighting of Disengaging Force	Equal variances assumed	,075	,786	,425	31	,674	,265	,623	-1,005	1,535
	Equal variances not assumed			,425	30,874	,674	,265	,623	-1,005	1,535
Weighting of Stability	Equal variances assumed	,350	,558	-,416	31	,680	-,173	,415	-1,019	,674
	Equal variances not assumed			-,410	23,288	,686	-,173	,422	-1,045	,699
Weighting of Complexity	Equal variances assumed	,908	,348	,599	31	,553	,294	,491	-,707	1,295
	Equal variances not assumed			,592	25,767	,559	,294	,497	-,727	1,316

2 Rankings of Concept A

2.1 Descriptive statistics

Affordance Level				Statistic	Std. Error
Concept A Friction Rank	Low Affordance	Mean		4,50	,736
		95% Confidence Interval for Mean	Lower Bound	2,93	
			Upper Bound	6,07	
		5% Trimmed Mean		4,44	
		Median		4,00	
		Variance		8,667	
		Std. Deviation		2,944	
		Minimum		0	
		Maximum		10	
		Range		10	
		Interquartile Range		5	
		Skewness		,511	,564
		Kurtosis		-,679	1,091
	High Affordance	Mean		3,88	,618
		95% Confidence Interval for Mean	Lower Bound	2,57	
			Upper Bound	5,19	
		5% Trimmed Mean		3,81	
		Median		3,00	
		Variance		6,485	
		Std. Deviation		2,547	
		Minimum		0	
		Maximum		9	
		Range		9	
		Interquartile Range		3	
		Skewness		,432	,550
		Kurtosis		-,152	1,063
Concept A Holding Force Rank	Low Affordance	Mean		7,81	,579
		95% Confidence Interval for Mean	Lower Bound	6,58	
			Upper Bound	9,05	
		5% Trimmed Mean		7,96	
		Median		8,00	
		Variance		5,363	
		Std. Deviation		2,316	
		Minimum		3	
		Maximum		10	
		Range		7	
		Interquartile Range		4	
		Skewness		-,808	,564
		Kurtosis		-,378	1,091

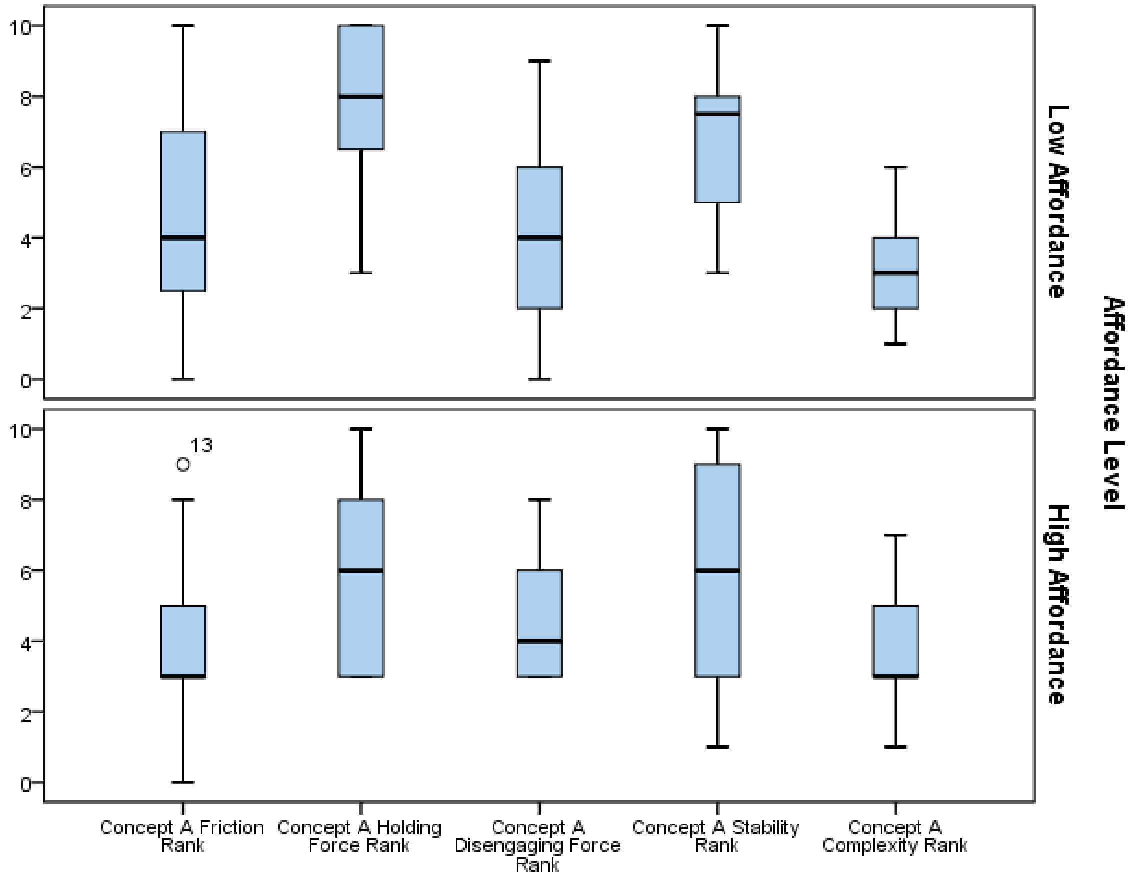
	High Affordance	Mean		6,00	,636
		95% Confidence Interval for Mean	Lower Bound	4,65	
			Upper Bound	7,35	
		5% Trimmed Mean		5,94	
		Median		6,00	
		Variance		6,875	
		Std. Deviation		2,622	
		Minimum		3	
		Maximum		10	
		Range		7	
		Interquartile Range		6	
		Skewness		,354	,550
		Kurtosis		-1,202	1,063
Concept A Disengaging Force Rank	Low Affordance	Mean		4,31	,656
		95% Confidence Interval for Mean	Lower Bound	2,91	
			Upper Bound	5,71	
		5% Trimmed Mean		4,29	
		Median		4,00	
		Variance		6,896	
		Std. Deviation		2,626	
		Minimum		0	
		Maximum		9	
		Range		9	
		Interquartile Range		5	
		Skewness		,343	,564
		Kurtosis		-,787	1,091
	High Affordance	Mean		4,59	,446
		95% Confidence Interval for Mean	Lower Bound	3,64	
			Upper Bound	5,53	
		5% Trimmed Mean		4,49	
		Median		4,00	
		Variance		3,382	
		Std. Deviation		1,839	
		Minimum		3	
		Maximum		8	
		Range		5	
		Interquartile Range		3	
		Skewness		,763	,550
		Kurtosis		-,761	1,063
Concept A Stability Rank	Low Affordance	Mean		6,75	,487
		95% Confidence Interval for Mean	Lower Bound	5,71	
			Upper Bound	7,79	
		5% Trimmed Mean		6,78	
		Median		7,50	
		Variance		3,800	

		Std. Deviation		1,949	
		Minimum		3	
		Maximum		10	
		Range		7	
		Interquartile Range		3	
		Skewness		-,339	,564
		Kurtosis		-,703	1,091
	High Affordance	Mean		5,82	,729
		95% Confidence Interval for Mean	Lower Bound	4,28	
			Upper Bound	7,37	
		5% Trimmed Mean		5,86	
		Median		6,00	
		Variance		9,029	
		Std. Deviation		3,005	
		Minimum		1	
		Maximum		10	
		Range		9	
		Interquartile Range		6	
		Skewness		-,059	,550
		Kurtosis		-1,372	1,063
Concept A Complexity Rank	Low Affordance	Mean		3,25	,335
		95% Confidence Interval for Mean	Lower Bound	2,54	
			Upper Bound	3,96	
		5% Trimmed Mean		3,22	
		Median		3,00	
		Variance		1,800	
		Std. Deviation		1,342	
		Minimum		1	
		Maximum		6	
		Range		5	
		Interquartile Range		2	
		Skewness		,426	,564
		Kurtosis		-,255	1,091
	High Affordance	Mean		3,59	,438
		95% Confidence Interval for Mean	Lower Bound	2,66	
			Upper Bound	4,52	
		5% Trimmed Mean		3,54	
		Median		3,00	
		Variance		3,257	
		Std. Deviation		1,805	
		Minimum		1	
		Maximum		7	
		Range		6	

	Interquartile Range	3	
	Skewness	,489	,550
	Kurtosis	-,702	1,063

2.2 Determining outliers

We produce boxplot for the distribution, to examine outliers.



Outliers found:

- Interface Friction; Participant 13

2.3 Normality Test (Shapiro-Wilk)

Affordance Level		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
Concept A Friction Rank	Low Affordance	,192	16	,116	,941	16	,358
	High Affordance	,224	17	,024	,927	17	,195
Concept A Holding Force Rank	Low Affordance	,203	16	,078	,866	16	,023
	High Affordance	,168	17	,200*	,878	17	,030
Concept A Disengaging Force Rank	Low Affordance	,186	16	,143	,929	16	,232
	High Affordance	,277	17	,001	,812	17	,003
Concept A Stability Rank	Low Affordance	,239	16	,015	,934	16	,283
	High Affordance	,149	17	,200*	,931	17	,228
Concept A Complexity Rank	Low Affordance	,199	16	,091	,944	16	,402
	High Affordance	,275	17	,001	,899	17	,064

Non-Normailties:

- Holding Force; HA + LA
- Disengaging Force; HA

2.4 Student T-Test

Affordance Level		N	Mean	Std. Deviation	Std. Error Mean
Concept A Friction Rank	Low Affordance	16	4,50	2,944	,736
	High Affordance	17	3,88	2,547	,618
Concept A Holding Force Rank	Low Affordance	16	7,81	2,316	,579
	High Affordance	17	6,00	2,622	,636
Concept A Disengaging Force Rank	Low Affordance	16	4,31	2,626	,656
	High Affordance	17	4,59	1,839	,446
Concept A Stability Rank	Low Affordance	16	6,75	1,949	,487
	High Affordance	17	5,82	3,005	,729
Concept A Complexity Rank	Low Affordance	16	3,25	1,342	,335
	High Affordance	17	3,59	1,805	,438

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Concept A Friction Rank	Equal variances assumed	,520	,476	,646	31	,523	,618	,956	-1,333	2,568
	Equal variances not assumed			,643	29,739	,525	,618	,961	-1,345	2,581
Concept A Holding Force Rank	Equal variances assumed	,289	,594	2,099	31	,044	1,813	,863	,052	3,573
	Equal variances not assumed			2,108	30,884	,043	1,813	,860	,058	3,567
Concept A Disengaging Force Rank	Equal variances assumed	1,630	,211	-,351	31	,728	-,276	,785	-1,877	1,326
	Equal variances not assumed			-,347	26,710	,731	-,276	,794	-1,905	1,354
Concept A Stability Rank	Equal variances assumed	4,162	,050	1,043	31	,305	,926	,888	-,885	2,737
	Equal variances not assumed			1,057	27,618	,300	,926	,877	-,871	2,723
Concept A Complexity Rank	Equal variances assumed	1,710	,201	-,608	31	,548	-,338	,556	-1,473	,797
	Equal variances not assumed			-,613	29,468	,544	-,338	,551	-1,465	,789

3 Rankings of Concept B

3.1 Descriptive statistics

Affordance Level				Statistic	Std. Error
Concept B Friction Rank	Low Affordance	Mean		6,31	,575
		95% Confidence Interval for Mean	Lower Bound	5,09	
			Upper Bound	7,54	
		5% Trimmed Mean		6,35	
		Median		7,00	
		Variance		5,296	
		Std. Deviation		2,301	
		Minimum		2	
		Maximum		10	
		Range		8	
		Interquartile Range		3	
		Skewness		-,437	,564
		Kurtosis		-,633	1,091
	High Affordance	Mean		7,35	,437
		95% Confidence Interval for Mean	Lower Bound	6,43	
			Upper Bound	8,28	
		5% Trimmed Mean		7,34	
		Median		8,00	
		Variance		3,243	
		Std. Deviation		1,801	
		Minimum		5	
		Maximum		10	
		Range		5	
		Interquartile Range		4	
		Skewness		-,312	,550
		Kurtosis		-1,551	1,063
Concept B Holding Force Rank	Low Affordance	Mean		6,63	,455
		95% Confidence Interval for Mean	Lower Bound	5,65	
			Upper Bound	7,60	
		5% Trimmed Mean		6,69	
		Median		7,00	
		Variance		3,317	
		Std. Deviation		1,821	
		Minimum		3	
		Maximum		9	
		Range		6	
		Interquartile Range		3	
		Skewness		-,494	,564
		Kurtosis		-,784	1,091

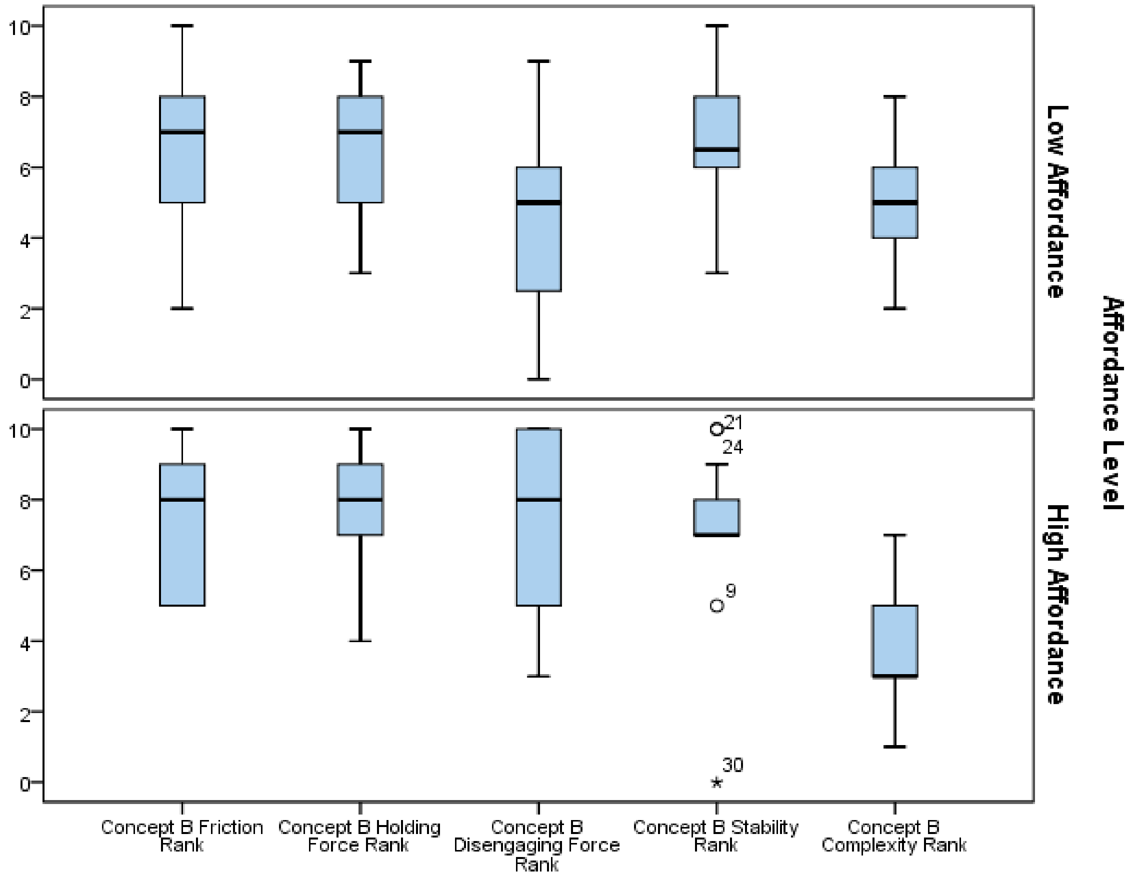
	High Affordance	Mean		7,71	,427
		95% Confidence Interval for Mean	Lower Bound	6,80	
			Upper Bound	8,61	
		5% Trimmed Mean		7,78	
		Median		8,00	
		Variance		3,096	
		Std. Deviation		1,759	
		Minimum		4	
		Maximum		10	
		Range		6	
		Interquartile Range		3	
		Skewness		-,505	,550
		Kurtosis		-,317	1,063
Concept B Disengaging Force Rank	Low Affordance	Mean		4,56	,639
		95% Confidence Interval for Mean	Lower Bound	3,20	
			Upper Bound	5,92	
		5% Trimmed Mean		4,57	
		Median		5,00	
		Variance		6,529	
		Std. Deviation		2,555	
		Minimum		0	
		Maximum		9	
		Range		9	
		Interquartile Range		4	
		Skewness		-,124	,564
		Kurtosis		-,735	1,091
	High Affordance	Mean		7,41	,636
		95% Confidence Interval for Mean	Lower Bound	6,06	
			Upper Bound	8,76	
		5% Trimmed Mean		7,51	
		Median		8,00	
		Variance		6,882	
		Std. Deviation		2,623	
		Minimum		3	
		Maximum		10	
		Range		7	
		Interquartile Range		5	
		Skewness		-,746	,550
		Kurtosis		-,885	1,063
Concept B Stability Rank	Low Affordance	Mean		6,69	,445
		95% Confidence Interval for Mean	Lower Bound	5,74	
			Upper Bound	7,64	
		5% Trimmed Mean		6,71	
		Median		6,50	
		Variance		3,163	

		Std. Deviation		1,778	
		Minimum		3	
		Maximum		10	
		Range		7	
		Interquartile Range		2	
		Skewness		-,353	,564
		Kurtosis		,122	1,091
	High Affordance	Mean		7,29	,547
		95% Confidence Interval for Mean	Lower Bound	6,13	
			Upper Bound	8,45	
		5% Trimmed Mean		7,55	
		Median		7,00	
		Variance		5,096	
		Std. Deviation		2,257	
		Minimum		0	
		Maximum		10	
		Range		10	
		Interquartile Range		2	
		Skewness		-2,151	,550
		Kurtosis		6,808	1,063
Concept B Complexity Rank	Low Affordance	Mean		4,88	,386
		95% Confidence Interval for Mean	Lower Bound	4,05	
			Upper Bound	5,70	
		5% Trimmed Mean		4,86	
		Median		5,00	
		Variance		2,383	
		Std. Deviation		1,544	
		Minimum		2	
		Maximum		8	
		Range		6	
		Interquartile Range		2	
		Skewness		,113	,564
		Kurtosis		,069	1,091
	High Affordance	Mean		4,00	,437
		95% Confidence Interval for Mean	Lower Bound	3,07	
			Upper Bound	4,93	
		5% Trimmed Mean		4,00	
		Median		3,00	
		Variance		3,250	
		Std. Deviation		1,803	
		Minimum		1	
		Maximum		7	
		Range		6	

	Interquartile Range	3	
	Skewness	,290	,550
	Kurtosis	-,933	1,063

3.2 Determining outliers

We produce boxplot for the distribution, to examine outliers.



Outliers found:

- Stability; Participant 9, 21, 24 and 30

3.3 Normality Test (Shapiro-Wilk)

Affordance Level		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
Concept B Friction Rank	Low Affordance	,180	16	,175	,943	16	,391
	High Affordance	,229	17	,019	,844	17	,009
Concept B Holding Force Rank	Low Affordance	,212	16	,052	,922	16	,179
	High Affordance	,155	17	,200*	,941	17	,335
Concept B Disengaging Force Rank	Low Affordance	,151	16	,200*	,970	16	,832
	High Affordance	,236	17	,013	,836	17	,007
Concept B Stability Rank	Low Affordance	,207	16	,065	,926	16	,212
	High Affordance	,331	17	,000	,762	17	,001
Concept B Complexity Rank	Low Affordance	,157	16	,200*	,968	16	,811
	High Affordance	,240	17	,010	,925	17	,182

Non-Normailties:

- Interface Friction; HA
- Disengaging Force; HA
- Stability; HA

3.4 Student T-Test

Affordance Level		N	Mean	Std. Deviation	Std. Error Mean
Concept B Friction Rank	Low Affordance	16	6,31	2,301	,575
	High Affordance	17	7,35	1,801	,437
Concept B Holding Force Rank	Low Affordance	16	6,63	1,821	,455
	High Affordance	17	7,71	1,759	,427
Concept B Disengaging Force Rank	Low Affordance	16	4,56	2,555	,639
	High Affordance	17	7,41	2,623	,636
Concept B Stability Rank	Low Affordance	16	6,69	1,778	,445
	High Affordance	17	7,29	2,257	,547
Concept B Complexity Rank	Low Affordance	16	4,88	1,544	,386
	High Affordance	17	4,00	1,803	,437

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference Lower	Upper
Concept B Friction Rank	Equal variances assumed	,812	,374	-1,451	31	,157	-1,040	,717	-2,503	,422
	Equal variances not assumed			-1,440	28,421	,161	-1,040	,722	-2,519	,438
Concept B Holding Force Rank	Equal variances assumed	,188	,668	-1,734	31	,093	-1,081	,623	-2,352	,190
	Equal variances not assumed			-1,732	30,711	,093	-1,081	,624	-2,354	,192
Concept B Disengaging Force Rank	Equal variances assumed	,014	,906	-3,158	31	,004	-2,849	,902	-4,690	-1,009
	Equal variances not assumed			-3,160	30,959	,004	-2,849	,902	-4,688	-1,010
Concept B Stability Rank	Equal variances assumed	,018	,894	-,854	31	,400	-,607	,710	-2,056	,842
	Equal variances not assumed			-,860	30,098	,397	-,607	,705	-2,047	,834
Concept B Complexity Rank	Equal variances assumed	1,338	,256	1,493	31	,146	,875	,586	-,320	2,070
	Equal variances not assumed			1,500	30,740	,144	,875	,583	-,315	2,065

4 Rankings of Concept C

4.1 Descriptive statistics

Affordance Level				Statistic	Std. Error
Concept C Friction Rank	Low Affordance	Mean		4,56	,701
		95% Confidence Interval for Mean	Lower Bound	3,07	
			Upper Bound	6,06	
		5% Trimmed Mean		4,46	
		Median		4,00	
		Variance		7,863	
		Std. Deviation		2,804	
		Minimum		1	
		Maximum		10	
		Range		9	
		Interquartile Range		5	
		Skewness		,329	,564
		Kurtosis		-,970	1,091
	High Affordance	Mean		3,35	,575
		95% Confidence Interval for Mean	Lower Bound	2,13	
			Upper Bound	4,57	
		5% Trimmed Mean		3,28	
		Median		3,00	
		Variance		5,618	
		Std. Deviation		2,370	
		Minimum		0	
		Maximum		8	
		Range		8	
		Interquartile Range		5	
		Skewness		,639	,550
		Kurtosis		-,716	1,063
Concept C Holding Force Rank	Low Affordance	Mean		4,75	,520
		95% Confidence Interval for Mean	Lower Bound	3,64	
			Upper Bound	5,86	
		5% Trimmed Mean		4,61	
		Median		5,00	
		Variance		4,333	
		Std. Deviation		2,082	
		Minimum		2	
		Maximum		10	
		Range		8	
		Interquartile Range		3	
		Skewness		,786	,564
		Kurtosis		1,462	1,091

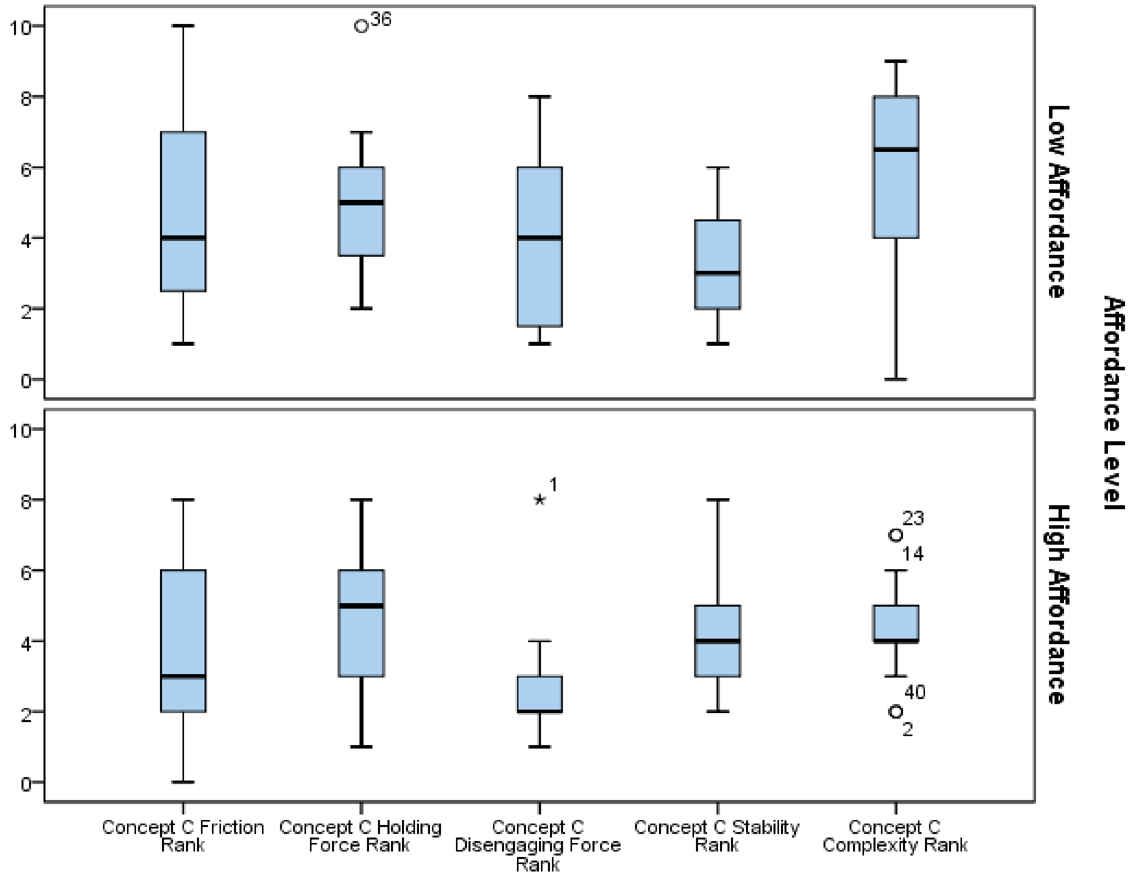
	High Affordance	Mean		4,41	,486
		95% Confidence Interval for Mean	Lower Bound	3,38	
			Upper Bound	5,44	
		5% Trimmed Mean		4,40	
		Median		5,00	
		Variance		4,007	
		Std. Deviation		2,002	
		Minimum		1	
		Maximum		8	
		Range		7	
		Interquartile Range		4	
		Skewness		-,065	,550
		Kurtosis		-,927	1,063
Concept C Disengaging Force Rank	Low Affordance	Mean		3,94	,655
		95% Confidence Interval for Mean	Lower Bound	2,54	
			Upper Bound	5,33	
		5% Trimmed Mean		3,88	
		Median		4,00	
		Variance		6,863	
		Std. Deviation		2,620	
		Minimum		1	
		Maximum		8	
		Range		7	
		Interquartile Range		5	
		Skewness		,484	,564
		Kurtosis		-1,100	1,091
	High Affordance	Mean		2,65	,383
		95% Confidence Interval for Mean	Lower Bound	1,84	
			Upper Bound	3,46	
		5% Trimmed Mean		2,44	
		Median		2,00	
		Variance		2,493	
		Std. Deviation		1,579	
		Minimum		1	
		Maximum		8	
		Range		7	
		Interquartile Range		1	
		Skewness		2,609	,550
		Kurtosis		8,664	1,063
Concept C Stability Rank	Low Affordance	Mean		3,44	,408
		95% Confidence Interval for Mean	Lower Bound	2,57	
			Upper Bound	4,31	
		5% Trimmed Mean		3,43	
		Median		3,00	
		Variance		2,663	

		Std. Deviation		1,632	
		Minimum		1	
		Maximum		6	
		Range		5	
		Interquartile Range		3	
		Skewness		,443	,564
		Kurtosis		-1,005	1,091
	High Affordance	Mean		4,24	,379
		95% Confidence Interval for Mean	Lower Bound	3,43	
			Upper Bound	5,04	
		5% Trimmed Mean		4,15	
		Median		4,00	
		Variance		2,441	
		Std. Deviation		1,562	
		Minimum		2	
		Maximum		8	
		Range		6	
		Interquartile Range		3	
		Skewness		,895	,550
		Kurtosis		,463	1,063
Concept C Complexity Rank	Low Affordance	Mean		5,56	,664
		95% Confidence Interval for Mean	Lower Bound	4,15	
			Upper Bound	6,98	
		5% Trimmed Mean		5,68	
		Median		6,50	
		Variance		7,063	
		Std. Deviation		2,658	
		Minimum		0	
		Maximum		9	
		Range		9	
		Interquartile Range		4	
		Skewness		-,676	,564
		Kurtosis		-,530	1,091
	High Affordance	Mean		4,53	,355
		95% Confidence Interval for Mean	Lower Bound	3,78	
			Upper Bound	5,28	
		5% Trimmed Mean		4,53	
		Median		4,00	
		Variance		2,140	
		Std. Deviation		1,463	
		Minimum		2	
		Maximum		7	
		Range		5	

	Interquartile Range	2	
	Skewness	,002	,550
	Kurtosis	-,238	1,063

4.2 Determining outliers

We produce boxplot for the distribution, to examine outliers.



Outliers found:

- Holding Force; Participant 36
- Disengaging Force; Participant 1
- Complexity; Participant 2, 14, 23 and 40

4.3 Normality Test (Shapiro-Wilk)

Affordance Level		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
Concept C Friction Rank	Low Affordance	,183	16	,158	,923	16	,191
	High Affordance	,265	17	,002	,900	17	,068
Concept C Holding Force Rank	Low Affordance	,149	16	,200*	,919	16	,163
	High Affordance	,145	17	,200*	,955	17	,533
Concept C Disengaging Force Rank	Low Affordance	,178	16	,188	,870	16	,027
	High Affordance	,294	17	,000	,691	17	,000
Concept C Stability Rank	Low Affordance	,186	16	,143	,896	16	,071
	High Affordance	,207	17	,051	,897	17	,061
Concept C Complexity Rank	Low Affordance	,206	16	,069	,912	16	,127
	High Affordance	,182	17	,137	,933	17	,245

Non-Normailties:

- Disengaging Force; LA + HA

4.4 Student T-Test

Affordance Level		N	Mean	Std. Deviation	Std. Error Mean
Concept C Friction Rank	Low Affordance	16	4,56	2,804	,701
	High Affordance	17	3,35	2,370	,575
Concept C Holding Force Rank	Low Affordance	16	4,75	2,082	,520
	High Affordance	17	4,41	2,002	,486
Concept C Disengaging Force Rank	Low Affordance	16	3,94	2,620	,655
	High Affordance	17	2,65	1,579	,383
Concept C Stability Rank	Low Affordance	16	3,44	1,632	,408
	High Affordance	17	4,24	1,562	,379
Concept C Complexity Rank	Low Affordance	16	5,56	2,658	,664
	High Affordance	17	4,53	1,463	,355

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference Lower	Upper
Concept C Friction Rank	Equal variances assumed	1,039	,316	1,341	31	,190	1,210	,902	-,630	3,049
	Equal variances not assumed			1,334	29,465	,192	1,210	,907	-,643	3,062
Concept C Holding Force Rank	Equal variances assumed	,133	,718	,476	31	,638	,338	,711	-1,112	1,788
	Equal variances not assumed			,475	30,683	,638	,338	,712	-1,114	1,790
Concept C Disengaging Force Rank	Equal variances assumed	5,136	,031	1,726	31	,094	1,290	,748	-,234	2,815
	Equal variances not assumed			1,701	24,342	,102	1,290	,759	-,274	2,855
Concept C Stability Rank	Equal variances assumed	,166	,686	-1,435	31	,161	-,798	,556	-1,932	,336
	Equal variances not assumed			-1,433	30,656	,162	-,798	,557	-1,934	,338
Concept C Complexity Rank	Equal variances assumed	8,190	,007	1,395	31	,173	1,033	,741	-,478	2,544
	Equal variances not assumed			1,372	23,019	,183	1,033	,753	-,525	2,591

5 Rankings of Concept D

5.1 Descriptive statistics

Affordance Level					Statistic	Std. Error
Concept D Friction Rank	Low Affordance	Mean			8,13	,539
		95% Confidence Interval for Mean	Lower Bound		6,98	
			Upper Bound		9,27	
		5% Trimmed Mean			8,31	
		Median			8,00	
		Variance			4,650	
		Std. Deviation			2,156	
		Minimum			3	
		Maximum			10	
		Range			7	
		Interquartile Range			2	
		Skewness			-1,324	,564
		Kurtosis			1,243	1,091
	High Affordance	Mean			5,65	,752
		95% Confidence Interval for Mean	Lower Bound		4,05	
			Upper Bound		7,24	
		5% Trimmed Mean			5,66	
		Median			7,00	
		Variance			9,618	
		Std. Deviation			3,101	
		Minimum			1	
		Maximum			10	
		Range			9	
		Interquartile Range			6	
		Skewness			-,010	,550
		Kurtosis			-1,437	1,063
Concept D Holding Force Rank	Low Affordance	Mean			7,38	,491
		95% Confidence Interval for Mean	Lower Bound		6,33	
			Upper Bound		8,42	
		5% Trimmed Mean			7,42	
		Median			7,50	
		Variance			3,850	
		Std. Deviation			1,962	
		Minimum			4	
		Maximum			10	
		Range			6	
		Interquartile Range			4	
		Skewness			-,180	,564
		Kurtosis			-1,116	1,091

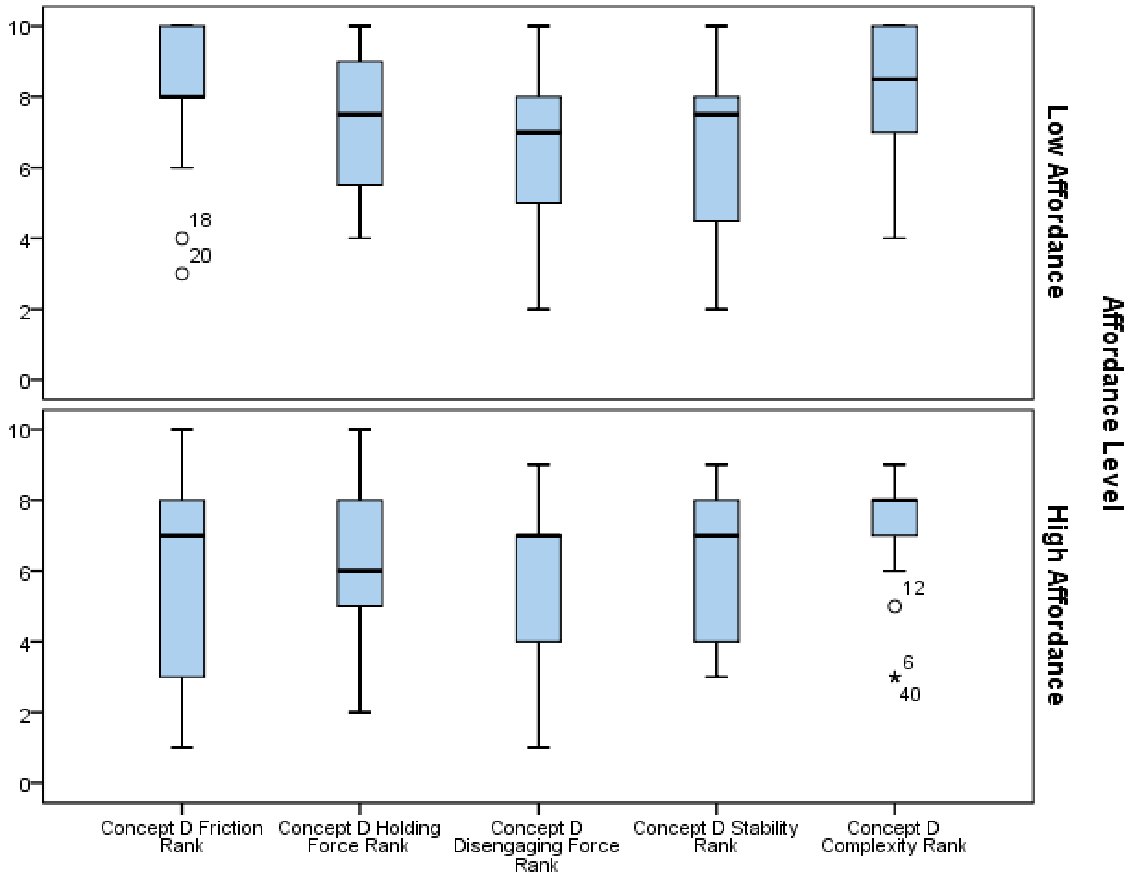
	High Affordance	Mean		6,35	,568
		95% Confidence Interval for Mean	Lower Bound	5,15	
			Upper Bound	7,56	
		5% Trimmed Mean		6,39	
		Median		6,00	
		Variance		5,493	
		Std. Deviation		2,344	
		Minimum		2	
		Maximum		10	
		Range		8	
		Interquartile Range		4	
		Skewness		-,120	,550
		Kurtosis		-,702	1,063
Concept D Disengaging Force Rank	Low Affordance	Mean		6,63	,598
		95% Confidence Interval for Mean	Lower Bound	5,35	
			Upper Bound	7,90	
		5% Trimmed Mean		6,69	
		Median		7,00	
		Variance		5,717	
		Std. Deviation		2,391	
		Minimum		2	
		Maximum		10	
		Range		8	
		Interquartile Range		3	
		Skewness		-,294	,564
		Kurtosis		-,391	1,091
	High Affordance	Mean		5,71	,617
		95% Confidence Interval for Mean	Lower Bound	4,40	
			Upper Bound	7,01	
		5% Trimmed Mean		5,78	
		Median		7,00	
		Variance		6,471	
		Std. Deviation		2,544	
		Minimum		1	
		Maximum		9	
		Range		8	
		Interquartile Range		5	
		Skewness		-,763	,550
		Kurtosis		-,867	1,063
Concept D Stability Rank	Low Affordance	Mean		6,56	,591
		95% Confidence Interval for Mean	Lower Bound	5,30	
			Upper Bound	7,82	
		5% Trimmed Mean		6,63	
		Median		7,50	
		Variance		5,596	

		Std. Deviation		2,366	
		Minimum		2	
		Maximum		10	
		Range		8	
		Interquartile Range		4	
		Skewness		-,538	,564
		Kurtosis		-,787	1,091
	High Affordance	Mean		6,06	,496
		95% Confidence Interval for Mean	Lower Bound	5,01	
			Upper Bound	7,11	
		5% Trimmed Mean		6,07	
		Median		7,00	
		Variance		4,184	
		Std. Deviation		2,045	
		Minimum		3	
		Maximum		9	
		Range		6	
		Interquartile Range		4	
		Skewness		-,040	,550
		Kurtosis		-1,624	1,063
Concept D Complexity Rank	Low Affordance	Mean		8,00	,508
		95% Confidence Interval for Mean	Lower Bound	6,92	
			Upper Bound	9,08	
		5% Trimmed Mean		8,11	
		Median		8,50	
		Variance		4,133	
		Std. Deviation		2,033	
		Minimum		4	
		Maximum		10	
		Range		6	
		Interquartile Range		3	
		Skewness		-,870	,564
		Kurtosis		-,128	1,091
	High Affordance	Mean		7,12	,461
		95% Confidence Interval for Mean	Lower Bound	6,14	
			Upper Bound	8,09	
		5% Trimmed Mean		7,24	
		Median		8,00	
		Variance		3,610	
		Std. Deviation		1,900	
		Minimum		3	
		Maximum		9	
		Range		6	

	Interquartile Range	2	
	Skewness	-1,243	,550
	Kurtosis	,884	1,063

5.2 Determining outliers

We produce boxplot for the distribution, to examine outliers.



Outliers found:

- Interface Friction; Participant 18 and 20
- Complexity; Participant 6, 12 and 40

5.3 Normality Test (Shapiro-Wilk)

Affordance Level		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
Concept D Friction Rank	Low Affordance	,289	16	,001	,798	16	,003
	High Affordance	,198	17	,075	,906	17	,086
Concept D Holding Force Rank	Low Affordance	,137	16	,200*	,930	16	,242
	High Affordance	,112	17	,200*	,969	17	,804
Concept D Disengaging Force Rank	Low Affordance	,187	16	,137	,940	16	,345
	High Affordance	,283	17	,001	,854	17	,012
Concept D Stability Rank	Low Affordance	,228	16	,025	,929	16	,231
	High Affordance	,255	17	,005	,868	17	,021
Concept D Complexity Rank	Low Affordance	,189	16	,131	,862	16	,021
	High Affordance	,240	17	,010	,831	17	,006

Non-Normailties:

- Interface Friction; LA
- Disengaging Force; HA
- Stability; HA
- Complexity; LA + HA

5.4 Student T-Test

Affordance Level		N	Mean	Std. Deviation	Std. Error Mean
Concept D Friction Rank	Low Affordance	16	8,13	2,156	,539
	High Affordance	17	5,65	3,101	,752
Concept D Holding Force Rank	Low Affordance	16	7,38	1,962	,491
	High Affordance	17	6,35	2,344	,568
Concept D Disengaging Force Rank	Low Affordance	16	6,63	2,391	,598
	High Affordance	17	5,71	2,544	,617
Concept D Stability Rank	Low Affordance	16	6,56	2,366	,591
	High Affordance	17	6,06	2,045	,496
Concept D Complexity Rank	Low Affordance	16	8,00	2,033	,508
	High Affordance	17	7,12	1,900	,461

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference Lower	Upper
Concept D Friction Rank	Equal variances assumed	6,195	,018	2,649	31	,013	2,478	,936	,570	4,386
	Equal variances not assumed			2,678	28,608	,012	2,478	,925	,584	4,372
Concept D Holding Force Rank	Equal variances assumed	,473	,497	1,354	31	,186	1,022	,755	-,518	2,562
	Equal variances not assumed			1,361	30,602	,183	1,022	,751	-,510	2,554
Concept D Disengaging Force Rank	Equal variances assumed	,410	,527	1,068	31	,294	,919	,861	-,836	2,674
	Equal variances not assumed			1,070	31,000	,293	,919	,859	-,833	2,671
Concept D Stability Rank	Equal variances assumed	,244	,625	,655	31	,517	,504	,768	-1,064	2,071
	Equal variances not assumed			,653	29,735	,519	,504	,772	-1,073	2,081
Concept D Complexity Rank	Equal variances assumed	,282	,599	1,289	31	,207	,882	,685	-,514	2,279
	Equal variances not assumed			1,286	30,485	,208	,882	,686	-,518	2,283

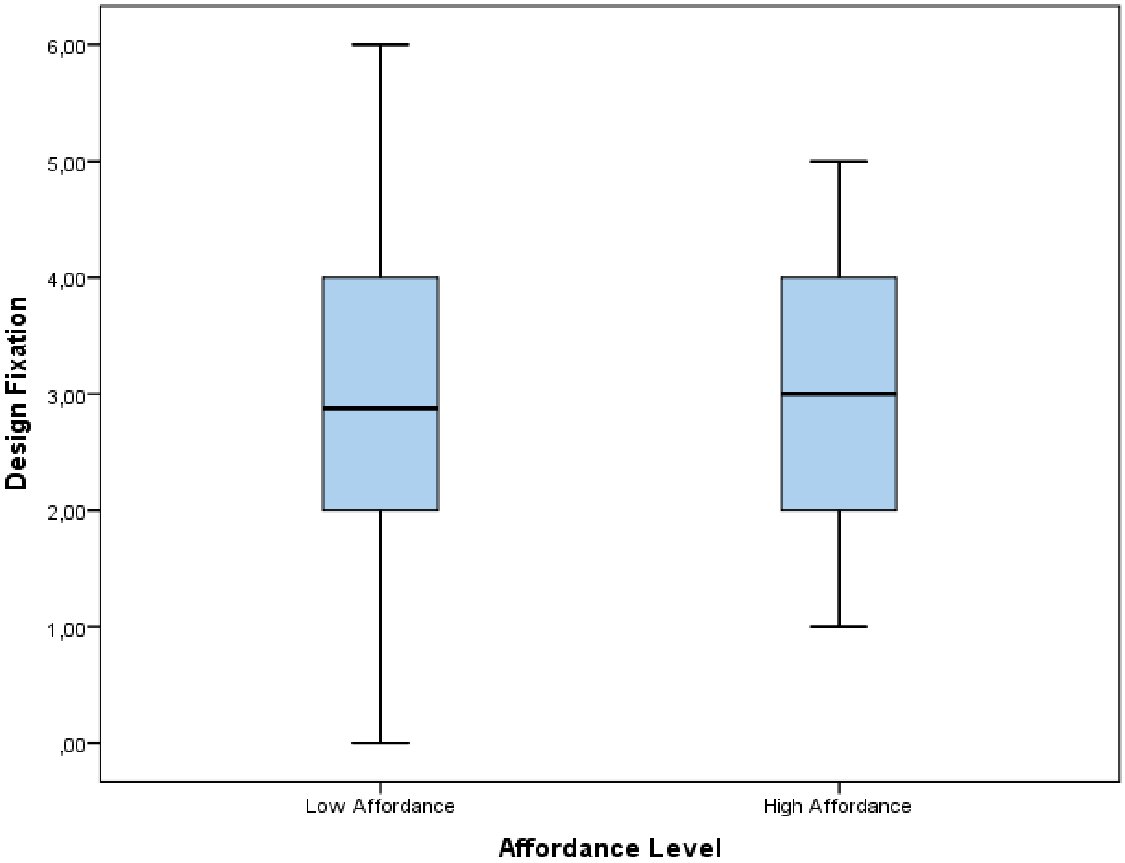
6 Design Fixation

6.1 Descriptive statistics

Affordance Level				Statistic	Std. Error
Design Fixation	Low Affordance	Mean		2,9427	,45164
		95% Confidence Interval for Mean	Lower Bound	1,9801	
			Upper Bound	3,9054	
		5% Trimmed Mean		2,9363	
		Median		2,8750	
		Variance		3,264	
		Std. Deviation		1,80655	
		Minimum		0,00	
		Maximum		6,00	
		Range		6,00	
		Interquartile Range		2,00	
		Skewness		,105	,564
		Kurtosis		-,330	1,091
	High Affordance	Mean		3,0735	,31635
		95% Confidence Interval for Mean	Lower Bound	2,4029	
			Upper Bound	3,7442	
		5% Trimmed Mean		3,0817	
		Median		3,0000	
		Variance		1,701	
		Std. Deviation		1,30433	
		Minimum		1,00	
		Maximum		5,00	
		Range		4,00	
		Interquartile Range		2,00	
		Skewness		-,348	,550
		Kurtosis		-,845	1,063

6.2 Determining outliers

We produce boxplot for the distribution, to examine outliers.



No outliers found.

6.3 Normality Test (Shapiro-Wilk)

Affordance Level		Kolmogorov-Smirnov[a] Statistic	df	Sig.	Shapiro-Wilk Statistic	df	Sig.
Design Fixation	Low Affordance	,113	16	,200*	,957	16	,612
	High Affordance	,173	17	,187	,915	17	,120

No non-normailties.

6.4 Student T-Test

Affordance Level		N	Mean	Std. Deviation	Std. Error Mean
Design Fixation	Low Affordance	16	2,9427	1,80655	,45164
	High Affordance	17	3,0735	1,30433	,31635

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference Lower	Upper
Design Fixation	Equal variances assumed	,961	,335	-,240	31	,812	-,13082	,54601	-1,24441	,98277
	Equal variances not assumed			-,237	27,193	,814	-,13082	,55141	-1,26184	1,00020

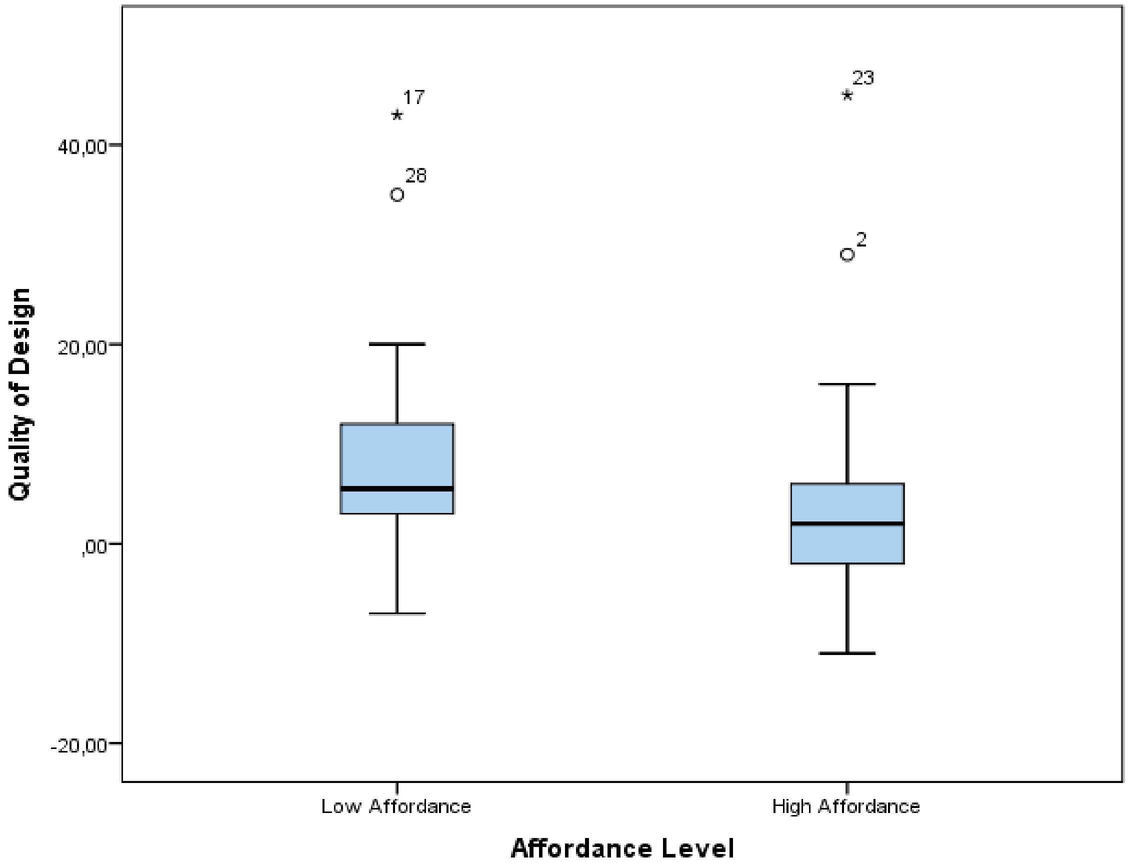
7 Quality of Design

7.1 Descriptive statistics

Affordance Level				Statistic	Std. Error
Quality of Design	Low Affordance	Mean		9,5990	3,33610
		95% Confidence Interval for Mean	Lower Bound	2,4882	
			Upper Bound	16,7097	
		5% Trimmed Mean		8,6655	
		Median		5,5000	
		Variance		178,073	
		Std. Deviation		13,34441	
		Minimum		-7,00	
		Maximum		43,00	
		Range		50,00	
		Interquartile Range		9,50	
		Skewness		1,417	,564
		Kurtosis		2,056	1,091
	High Affordance	Mean		5,2794	3,48130
		95% Confidence Interval for Mean	Lower Bound	-2,1006	
			Upper Bound	12,6594	
		5% Trimmed Mean		3,9771	
		Median		2,0000	
		Variance		206,030	
		Std. Deviation		14,35376	
		Minimum		-11,00	
		Maximum		45,00	
		Range		56,00	
		Interquartile Range		14,75	
		Skewness		1,577	,550
		Kurtosis		2,780	1,063

7.2 Determining outliers

We produce boxplot for the distribution, to examine outliers.



Outliers found

- Participant 17, 28 for low affordance
- Participant 2 and 23 for High affordance

7.3 Normality Test (Shapiro-Wilk)

Affordance Level		Kolmogorov-Smirnov[a] Statistic	Kolmogorov-Smirnov[a] df	Kolmogorov-Smirnov[a] Sig.	Shapiro-Wilk Statistic	Shapiro-Wilk df	Shapiro-Wilk Sig.
Quality of Design	Low Affordance	,212	16	,053	,847	16	,012
	High Affordance	,245	17	,008	,855	17	,013

Non-normailties in both conditions.

7.4 Student T-Test

Affordance Level		N	Mean	Std. Deviation	Std. Error Mean
Quality of Design	Low Affordance	16	9,5990	13,34441	3,33610
	High Affordance	17	5,2794	14,35376	3,48130

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference Lower	95% Confidence Interval of the Difference Upper
Quality of Design	Equal variances assumed	,038	,848	,894	31	,378	4,31955	4,83271	-5,53684	14,17593
	Equal variances not assumed			,896	30,997	,377	4,31955	4,82172	-5,51447	14,15356

8 Gender-sorted Weightings

8.1 Descriptive statistics

Gender				Statistic	Std. Error
Weighting of Interface Friction	Male	Mean		,54	,462
		95% Confidence Interval for Mean	Lower Bound	-,47	
			Upper Bound	1,54	
		5% Trimmed Mean		,54	
		Median		1,00	
		Variance		2,769	
		Std. Deviation		1,664	
		Minimum		-2	
		Maximum		3	
		Range		5	
		Interquartile Range		3	
		Skewness		-,272	,616
		Kurtosis		-1,240	1,191
	Female	Mean		-,09	,530
		95% Confidence Interval for Mean	Lower Bound	-1,27	
			Upper Bound	1,09	
		5% Trimmed Mean		-,10	
		Median		-1,00	
		Variance		3,091	
		Std. Deviation		1,758	
		Minimum		-2	
		Maximum		2	
		Range		4	
		Interquartile Range		4	
		Skewness		,302	,661
		Kurtosis		-1,896	1,279
Weighting of Holding Force	Male	Mean		2,23	,323
		95% Confidence Interval for Mean	Lower Bound	1,53	
			Upper Bound	2,94	
		5% Trimmed Mean		2,37	
		Median		3,00	
		Variance		1,359	
		Std. Deviation		1,166	
		Minimum		-1	
		Maximum		3	
		Range		4	
		Interquartile Range		1	
		Skewness		-2,017	,616
		Kurtosis		4,562	1,191

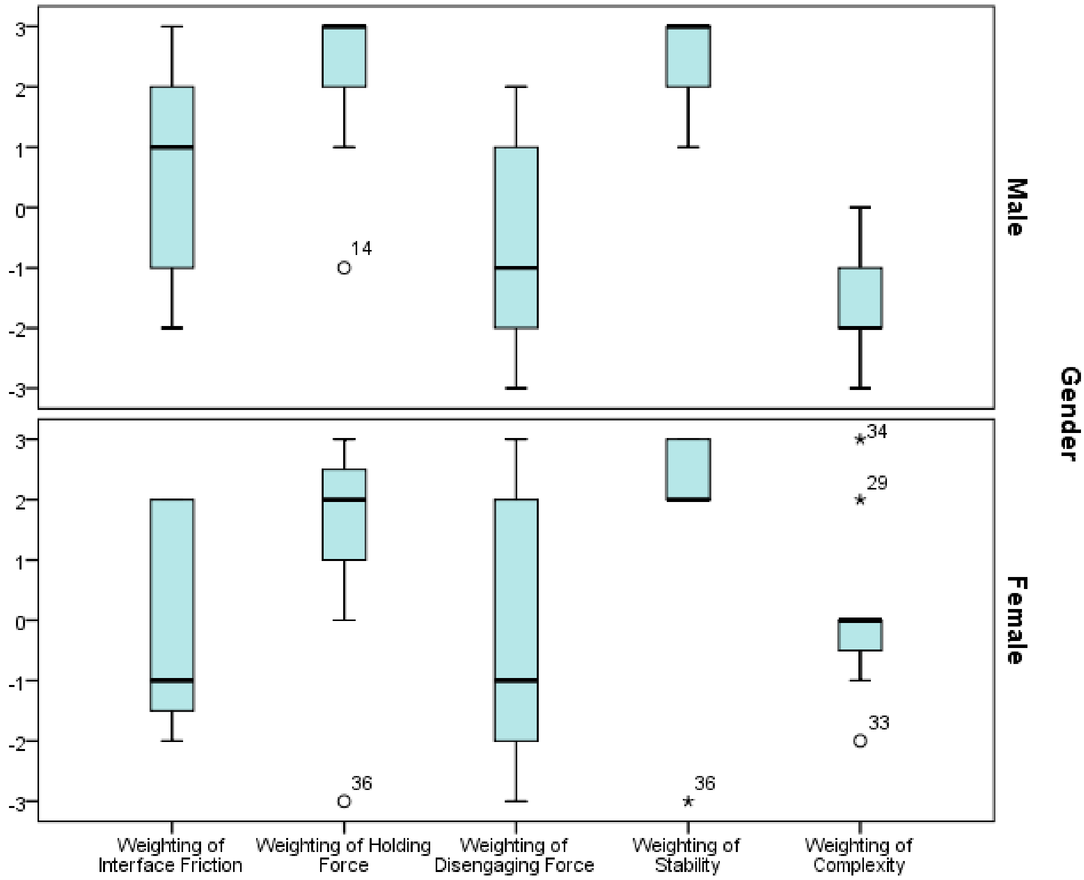
	Female	Mean		1,45	,545
		95% Confidence Interval for Mean	Lower Bound	,24	
			Upper Bound	2,67	
		5% Trimmed Mean		1,62	
		Median		2,00	
		Variance		3,273	
		Std. Deviation		1,809	
		Minimum		-3	
		Maximum		3	
		Range		6	
		Interquartile Range		3	
		Skewness		-1,706	,661
		Kurtosis		3,027	1,279
Weighting of Disengaging Force	Male	Mean		-,69	,499
		95% Confidence Interval for Mean	Lower Bound	-1,78	
			Upper Bound	,39	
		5% Trimmed Mean		-,71	
		Median		-1,00	
		Variance		3,231	
		Std. Deviation		1,797	
		Minimum		-3	
		Maximum		2	
		Range		5	
		Interquartile Range		4	
		Skewness		-,037	,616
		Kurtosis		-1,595	1,191
	Female	Mean		-,09	,639
		95% Confidence Interval for Mean	Lower Bound	-1,51	
			Upper Bound	1,33	
		5% Trimmed Mean		-,10	
		Median		-1,00	
		Variance		4,491	
		Std. Deviation		2,119	
		Minimum		-3	
		Maximum		3	
		Range		6	
		Interquartile Range		4	
		Skewness		,145	,661
		Kurtosis		-1,777	1,279
Weighting of Stability	Male	Mean		2,38	,213
		95% Confidence Interval for Mean	Lower Bound	1,92	
			Upper Bound	2,85	
		5% Trimmed Mean		2,43	
		Median		3,00	
		Variance		,590	

		Std. Deviation		,768	
		Minimum		1	
		Maximum		3	
		Range		2	
		Interquartile Range		1	
		Skewness		-,849	,616
		Kurtosis		-,580	1,191
	Female	Mean		2,00	,522
		95% Confidence Interval for Mean	Lower Bound	,84	
			Upper Bound	3,16	
		5% Trimmed Mean		2,22	
		Median		2,00	
		Variance		3,000	
		Std. Deviation		1,732	
		Minimum		-3	
		Maximum		3	
		Range		6	
		Interquartile Range		1	
		Skewness		-2,823	,661
		Kurtosis		8,667	1,279
Weighting of Complexity	Male	Mean		-1,38	,266
		95% Confidence Interval for Mean	Lower Bound	-1,97	
			Upper Bound	-,80	
		5% Trimmed Mean		-1,37	
		Median		-2,00	
		Variance		,923	
		Std. Deviation		,961	
		Minimum		-3	
		Maximum		0	
		Range		3	
		Interquartile Range		2	
		Skewness		,280	,616
		Kurtosis		-,891	1,191
	Female	Mean		,09	,415
		95% Confidence Interval for Mean	Lower Bound	-,83	
			Upper Bound	1,01	
		5% Trimmed Mean		,05	
		Median		0,00	
		Variance		1,891	
		Std. Deviation		1,375	
		Minimum		-2	
		Maximum		3	
		Range		5	

	Interquartile Range	1	
	Skewness	,932	,661
	Kurtosis	1,312	1,279

8.2 Determining outliers

We produce boxplot for the distribution, to examine outliers.



Outliers found:

- Interface Friction;
- Holding Force; Participant 14 and 36
- Disengaging Force;
- Stability; Participant 36
- Complexity; Participant 29, 33 and 34

8.3 Normality Test (Shapiro-Wilk)

Gender		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
Weighting of Interface Friction	Male	,195	13	,190	,917	13	,226
	Female	,246	11	,061	,799	11	,009
Weighting of Holding Force	Male	,284	13	,005	,702	13	,001
	Female	,346	11	,001	,774	11	,004
Weighting of Disengaging Force	Male	,211	13	,116	,889	13	,094
	Female	,211	11	,183	,885	11	,119
Weighting of Stability	Male	,327	13	,000	,756	13	,002
	Female	,409	11	,000	,569	11	,000
Weighting of Complexity	Male	,278	13	,007	,862	13	,041
	Female	,345	11	,001	,855	11	,049

Non-Normailties:

- Interface Friction; HA + LA
- Holding Force; HA + LA
- Disengaging Force; LA
- Stability; HA + LA
- Complexity; HA + LA

8.4 Student T-Test

Gender		N	Mean	Std. Deviation	Std. Error Mean
Weighting of Interface Friction	Male	13	,54	1,664	,462
	Female	11	-,09	1,758	,530
Weighting of Holding Force	Male	13	2,23	1,166	,323
	Female	11	1,45	1,809	,545
Weighting of Disengaging Force	Male	13	-,69	1,797	,499
	Female	11	-,09	2,119	,639
Weighting of Stability	Male	13	2,38	,768	,213
	Female	11	2,00	1,732	,522
Weighting of Complexity	Male	13	-1,38	,961	,266
	Female	11	,09	1,375	,415

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference Lower	Upper
Weighting of Interface Friction	Equal variances assumed	,151	,702	,900	22	,378	,629	,700	-,821	2,080
	Equal variances not assumed			,895	20,900	,381	,629	,703	-,833	2,091
Weighting of Holding Force	Equal variances assumed	1,675	,209	1,269	22	,218	,776	,612	-,492	2,045
	Equal variances not assumed			1,224	16,558	,238	,776	,634	-,564	2,117
Weighting of Disengaging Force	Equal variances assumed	1,232	,279	-,753	22	,460	-,601	,799	-2,258	1,056
	Equal variances not assumed			-,742	19,774	,467	-,601	,810	-2,293	1,090
Weighting of Stability	Equal variances assumed	,357	,556	,723	22	,477	,385	,532	-,718	1,488
	Equal variances not assumed			,682	13,297	,507	,385	,564	-,831	1,600
Weighting of Complexity	Equal variances assumed	,036	,851	-3,085	22	,005	-1,476	,478	-2,467	-,484
	Equal variances not assumed			-2,994	17,482	,008	-1,476	,493	-2,513	-,438

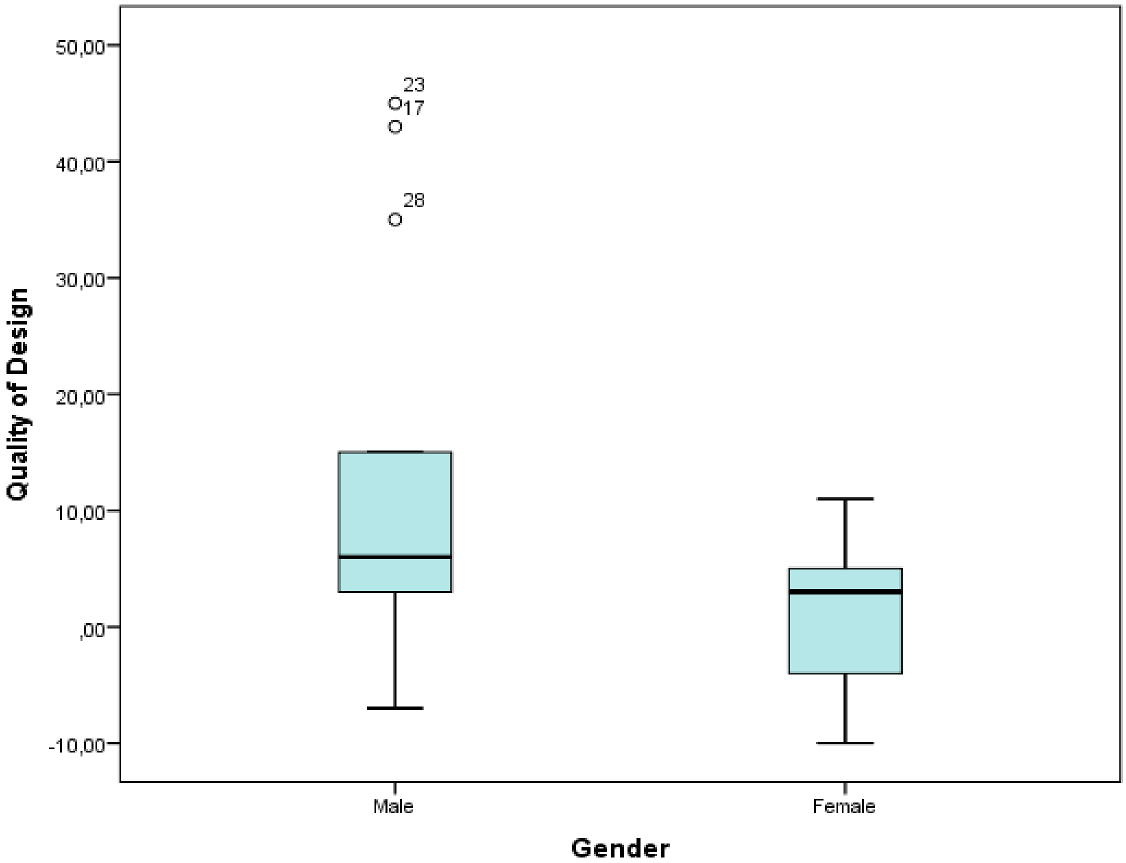
9 Gender-sorted Quality of Design

9.1 Descriptive statistics

Gender				Statistic	Std. Error
Quality of Design	Male	Mean		12,8462	4,75805
		95% Confidence Interval for Mean	Lower Bound	2,4793	
			Upper Bound	23,2131	
		5% Trimmed Mean		12,1624	
		Median		6,0000	
		Variance		294,308	
		Std. Deviation		17,15540	
		Minimum		-7,00	
		Maximum		45,00	
		Range		52,00	
		Interquartile Range		23,50	
		Skewness		1,088	,616
		Kurtosis		-,125	1,191
	Female	Mean		1,3636	2,08576
		95% Confidence Interval for Mean	Lower Bound	-3,2837	
			Upper Bound	6,0110	
		5% Trimmed Mean		1,4596	
		Median		3,0000	
		Variance		47,855	
		Std. Deviation		6,91770	
		Minimum		-10,00	
		Maximum		11,00	
		Range		21,00	
		Interquartile Range		12,00	
		Skewness		-,366	,661
		Kurtosis		-,878	1,279

9.2 Determining outliers

We produce boxplot for the distribution, to examine outliers.



Outliers found

- Males: Participant 17 and 23 and 28

9.3 Normality Test (Shapiro-Wilk)

Gender		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
Quality of Design	Male	,270	13	,010	,833	13	,017
	Female	,173	11	,200*	,931	11	,421

Non-normality in male sample.

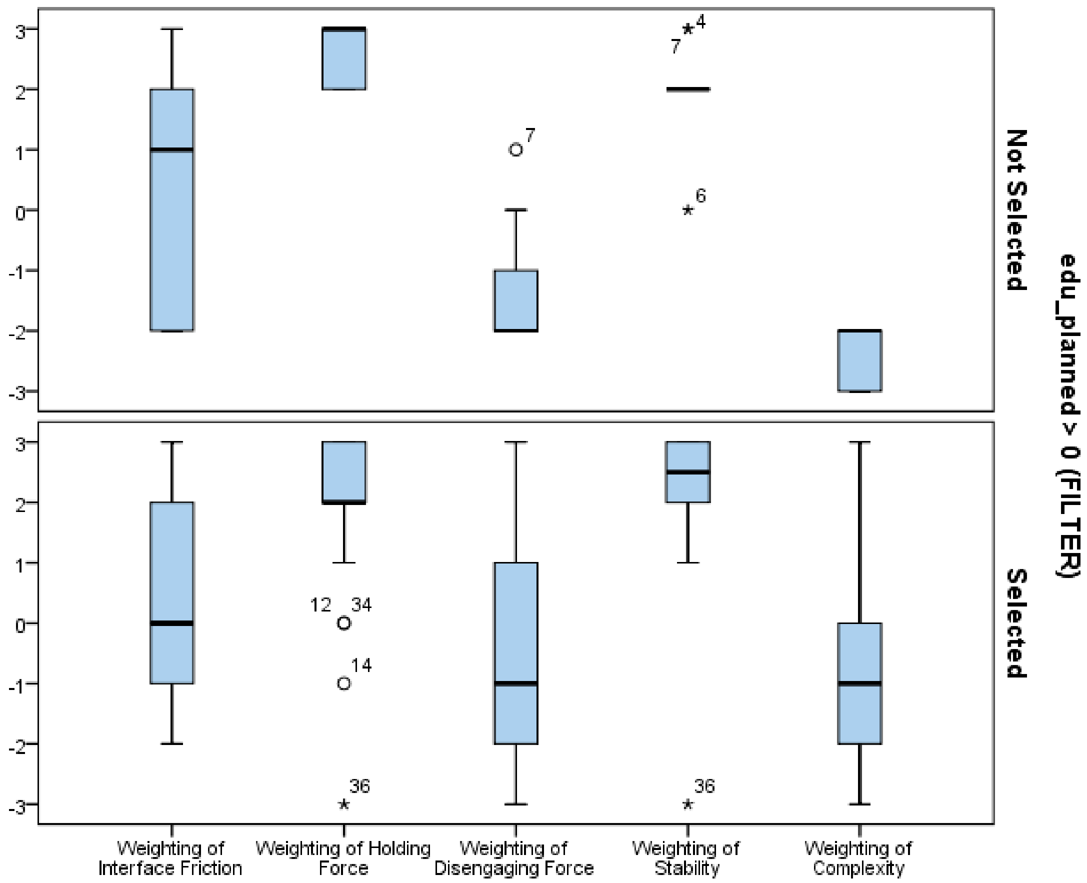
9.4 Student T-Test

Gender		N	Mean	Std. Deviation	Std. Error Mean
Quality of Design	Male	13	12,8462	17,15540	4,75805
	Female	11	1,3636	6,91770	2,08576

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Quality of Design	Equal variances assumed	5,898	,024	2,076	22	,050	11,48252	5,53110	,01172	22,95331
	Equal variances not assumed			2,210	16,331	,042	11,48252	5,19514	,48745	22,47759

10 STUDENT vs. PRACTITIONER: Weightings

We produce boxplot for the distribution, to examine outliers.



We check for normality

edu_planned > 0 (FILTER)		Kolmogorov-Smirnov[a] Statistic	df	Sig.	Shapiro-Wilk Statistic	df	Sig.
Weighting of Interface Friction	Not Selected	,215	9	,200*	,869	9	,119
	Selected	,223	24	,003	,865	24	,004
Weighting of Holding Force	Not Selected	,414	9	,000	,617	9	,000
	Selected	,325	24	,000	,733	24	,000
Weighting of Disengaging Force	Not Selected	,317	9	,009	,767	9	,009
	Selected	,185	24	,033	,905	24	,028
Weighting of Stability	Not Selected	,389	9	,000	,728	9	,003
	Selected	,311	24	,000	,598	24	,000
Weighting of Complexity	Not Selected	,414	9	,000	,617	9	,000
	Selected	,219	24	,004	,880	24	,008

Descriptive statistics:

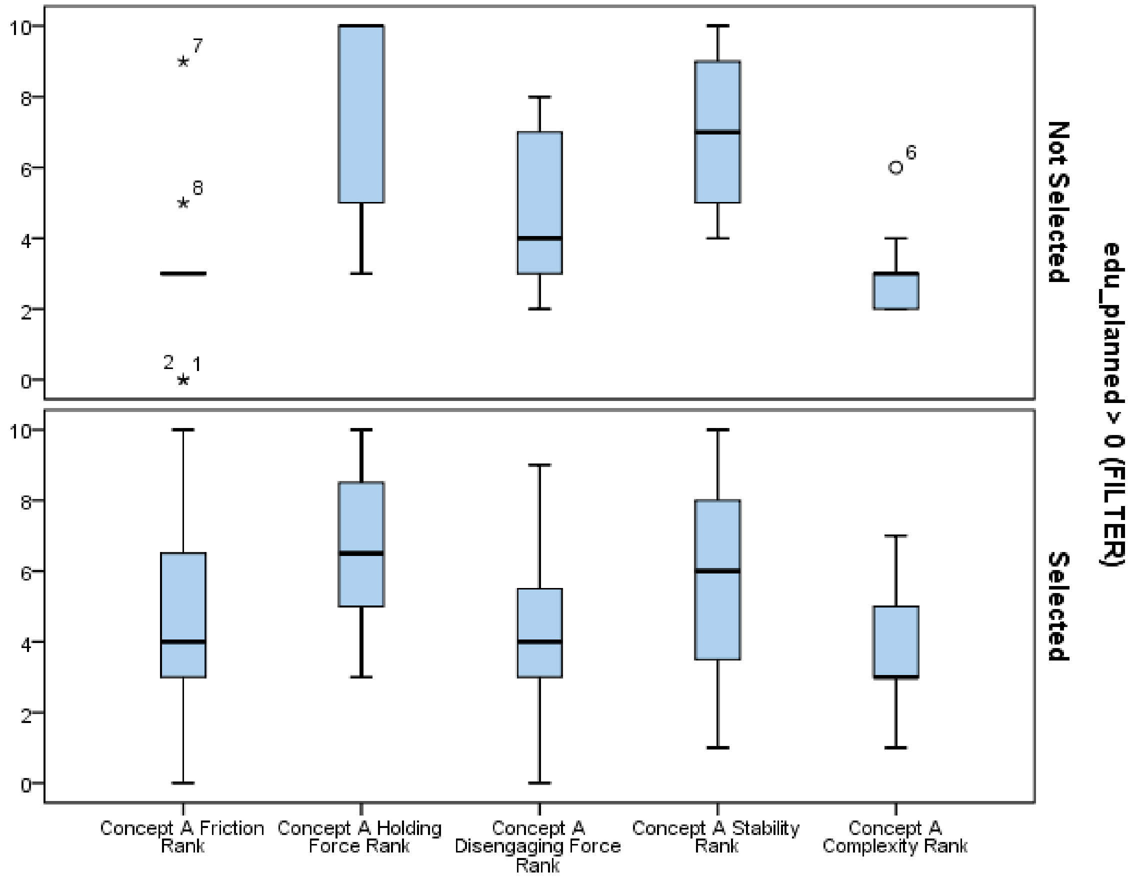
edu_planned > 0 (FILTER)		N	Mean	Std. Deviation	Std. Error Mean
Weighting of Interface Friction	Not Selected	9	,44	2,068	,689
	Selected	24	,25	1,700	,347
Weighting of Holding Force	Not Selected	9	2,67	,500	,167
	Selected	24	1,88	1,513	,309
Weighting of Disengaging Force	Not Selected	9	-1,22	1,093	,364
	Selected	24	-,42	1,932	,394
Weighting of Stability	Not Selected	9	2,00	,866	,289
	Selected	24	2,21	1,285	,262
Weighting of Complexity	Not Selected	9	-2,33	,500	,167
	Selected	24	-,71	1,367	,279

Independent samples t-test:

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference Lower	Upper
Weighting of Interface Friction	Equal variances assumed	,477	,495	,276	31	,784	,194	,705	-1,242	1,631
	Equal variances not assumed			,252	12,295	,805	,194	,772	-1,483	1,872
Weighting of Holding Force	Equal variances assumed	2,557	,120	1,526	31	,137	,792	,519	-,267	1,850
	Equal variances not assumed			2,256	30,831	,031	,792	,351	,076	1,507
Weighting of Disengaging Force	Equal variances assumed	8,140	,008	-1,175	31	,249	-,806	,686	-2,204	,593
	Equal variances not assumed			-1,501	25,536	,146	-,806	,537	-1,910	,299
Weighting of Stability	Equal variances assumed	,901	,350	-,448	31	,658	-,208	,465	-1,158	,741
	Equal variances not assumed			-,534	21,547	,599	-,208	,390	-1,018	,601
Weighting of Complexity	Equal variances assumed	4,927	,034	-3,452	31	,002	-1,625	,471	-2,585	-,665
	Equal variances not assumed			-5,001	30,996	,000	-1,625	,325	-2,288	-,962

11 STUDENT vs. PRACTITIONER: Rankings of Concept A

We produce boxplot for the distribution, to examine outliers.



We check for normality

edu_planned > 0 (FILTER)		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
Concept A Friction Rank	Not Selected	,311	9	,012	,832	9	,047
	Selected	,163	24	,100	,956	24	,364
Concept A Holding Force Rank	Not Selected	,328	9	,006	,735	9	,004
	Selected	,099	24	,200*	,924	24	,073
Concept A Disengaging Force Rank	Not Selected	,222	9	,200*	,889	9	,195
	Selected	,143	24	,200*	,946	24	,223
Concept A Stability Rank	Not Selected	,177	9	,200*	,937	9	,548
	Selected	,194	24	,020	,940	24	,159
Concept A Complexity Rank	Not Selected	,278	9	,044	,776	9	,011
	Selected	,220	24	,004	,930	24	,098

Descriptive statistics:

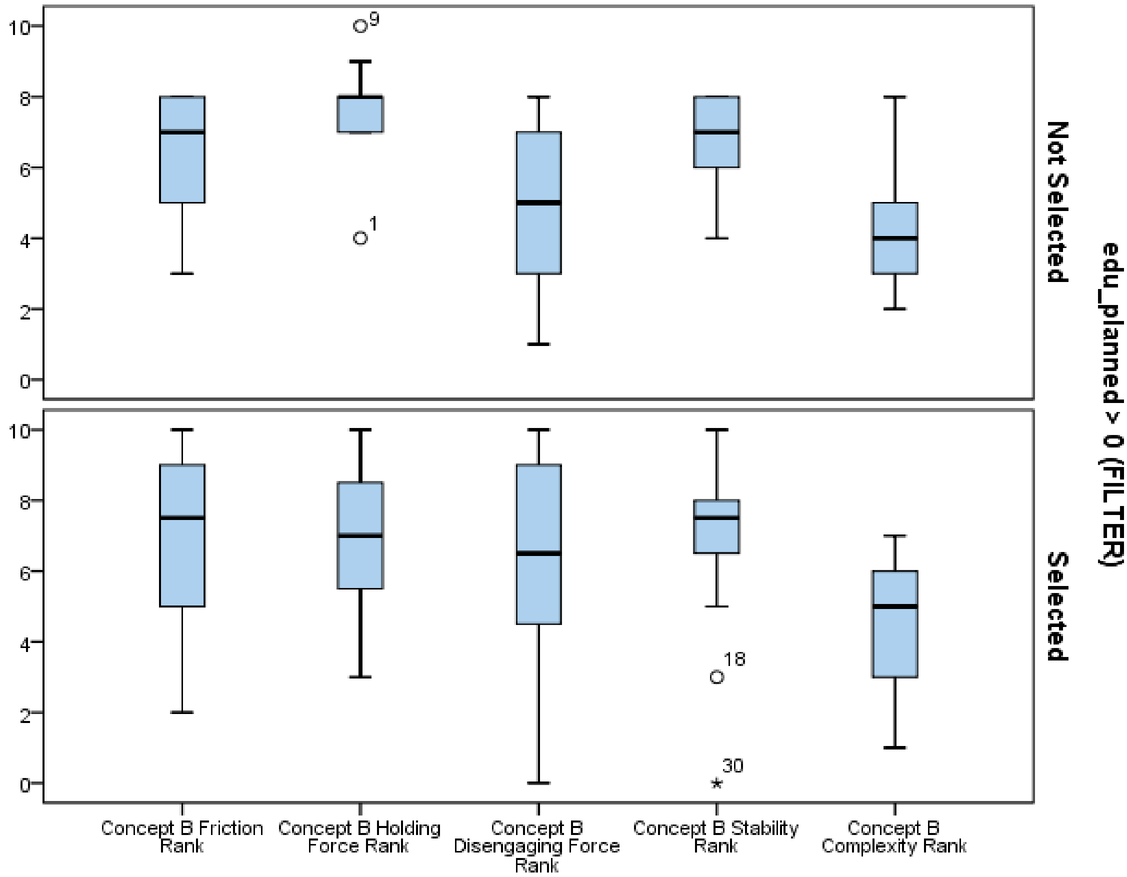
edu_planned > 0 (FILTER)		N	Mean	Std. Deviation	Std. Error Mean
Concept A Friction Rank	Not Selected	9	3,22	2,682	,894
	Selected	24	4,54	2,702	,552
Concept A Holding Force Rank	Not Selected	9	7,67	3,122	1,041
	Selected	24	6,58	2,394	,489
Concept A Disengaging Force Rank	Not Selected	9	4,67	2,179	,726
	Selected	24	4,38	2,281	,466
Concept A Stability Rank	Not Selected	9	7,11	2,088	,696
	Selected	24	5,96	2,678	,547
Concept A Complexity Rank	Not Selected	9	3,00	1,323	,441
	Selected	24	3,58	1,666	,340

Independent samples t-test:

		Levene's Test for Equality of Variances		t-test for Equality of Means					95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Concept A Friction Rank	Equal variances assumed	,708	,406	-1,252	31	,220	-1,319	1,054	-3,470	,831
	Equal variances not assumed			-1,256	14,518	,229	-1,319	1,051	-3,565	,926
Concept A Holding Force	Equal variances assumed	1,810	,188	1,065	31	,295	1,083	1,017	-,991	3,157
	Equal variances not assumed			,942	11,718	,365	1,083	1,150	-1,429	3,595
Concept A Disengaging	Equal variances assumed	,004	,952	,331	31	,743	,292	,881	-1,506	2,089
	Equal variances not assumed			,338	15,037	,740	,292	,863	-1,547	2,130
Concept A Stability Rank	Equal variances assumed	1,029	,318	1,162	31	,254	1,153	,992	-,871	3,177
	Equal variances not assumed			1,302	18,467	,209	1,153	,885	-,703	3,009
Concept A Complexity	Equal variances assumed	1,569	,220	-,942	31	,354	-,583	,619	-1,846	,680
	Equal variances not assumed			-1,048	18,116	,309	-,583	,557	-1,753	,586

12 STUDENT vs. PRACTITIONER: Rankings of Concept B

We produce boxplot for the distribution, to examine outliers.



We check for normality

edu_planned > 0 (FILTER)		Kolmogorov-Smirnov[a] Statistic	df	Sig.	Shapiro-Wilk Statistic	df	Sig.
Concept B Friction Rank	Not Selected	,258	9	,086	,821	9	,036
	Selected	,170	24	,071	,922	24	,064
Concept B Holding Force Rank	Not Selected	,246	9	,123	,872	9	,128
	Selected	,158	24	,125	,955	24	,345
Concept B Disengaging Force Rank	Not Selected	,217	9	,200*	,914	9	,345
	Selected	,154	24	,144	,922	24	,065
Concept B Stability Rank	Not Selected	,178	9	,200*	,899	9	,246
	Selected	,220	24	,004	,852	24	,002
Concept B Complexity Rank	Not Selected	,143	9	,200*	,944	9	,620
	Selected	,184	24	,035	,932	24	,107

Descriptive statistics:

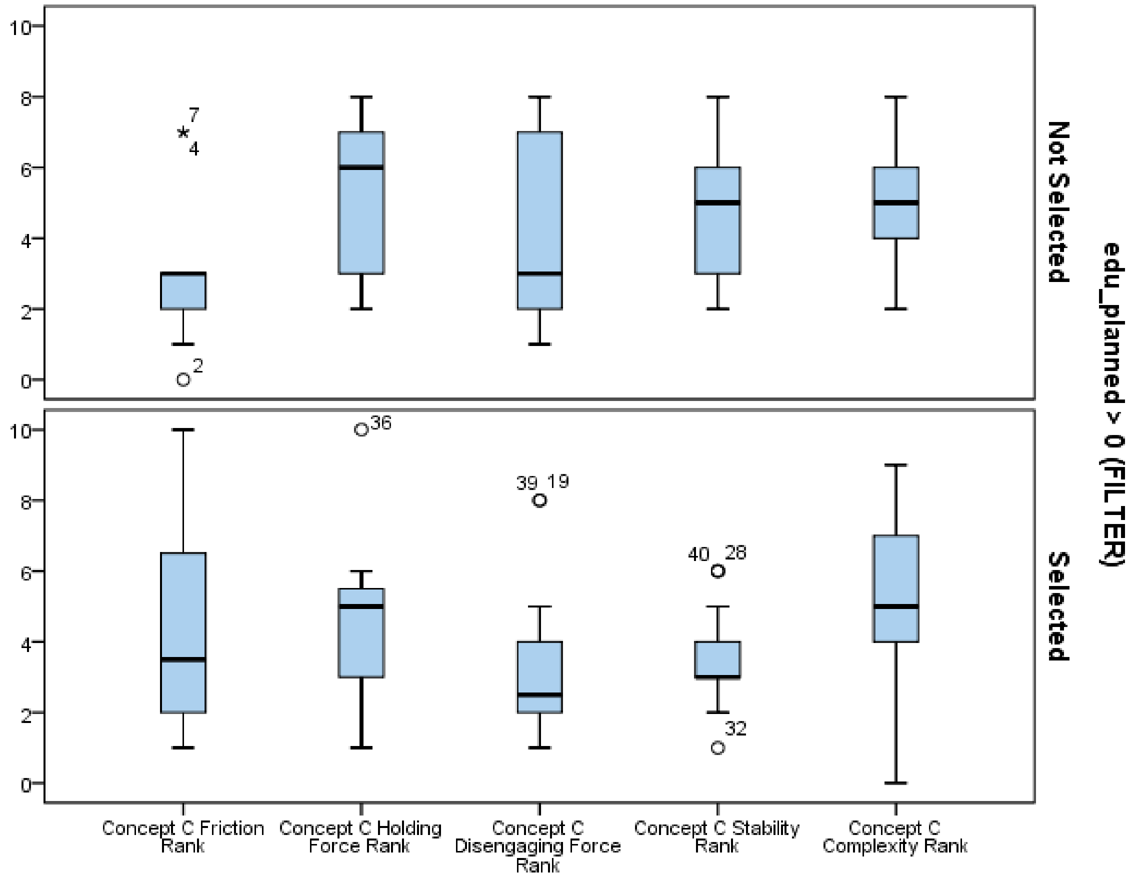
edu_planned > 0 (FILTER)		N	Mean	Std. Deviation	Std. Error Mean
Concept B Friction Rank	Not Selected	9	6,33	1,871	,624
	Selected	24	7,04	2,177	,444
Concept B Holding Force Rank	Not Selected	9	7,67	1,658	,553
	Selected	24	7,00	1,911	,390
Concept B Disengaging Force Rank	Not Selected	9	4,89	2,522	,841
	Selected	24	6,46	3,007	,614
Concept B Stability Rank	Not Selected	9	6,56	1,424	,475
	Selected	24	7,17	2,220	,453
Concept B Complexity Rank	Not Selected	9	4,33	1,936	,645
	Selected	24	4,46	1,668	,340

Independent samples t-test:

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Concept B Friction Rank	Equal variances assumed	,148	,703	-,862	31	,395	-,708	,822	-2,384	,967
	Equal variances not assumed			-,925	16,687	,368	-,708	,766	-2,326	,909
Concept B Holding Force Rank	Equal variances assumed	1,303	,262	,922	31	,363	,667	,723	-,807	2,141
	Equal variances not assumed			,985	16,527	,339	,667	,677	-,764	2,097
Concept B Disengaging Force Rank	Equal variances assumed	,561	,459	-1,390	31	,175	-1,569	1,129	-3,873	,734
	Equal variances not assumed			-1,508	17,110	,150	-1,569	1,041	-3,765	,626
Concept B Stability Rank	Equal variances assumed	,369	,548	-,765	31	,450	-,611	,799	-2,241	1,019
	Equal variances not assumed			-,931	22,674	,362	-,611	,656	-1,970	,747
Concept B Complexity Rank	Equal variances assumed	,030	,865	-,184	31	,855	-,125	,680	-1,513	1,263
	Equal variances not assumed			-,171	12,726	,867	-,125	,730	-1,705	1,455

13 STUDENT vs. PRACTITIONER: Rankings of Concept C

We produce boxplot for the distribution, to examine outliers.



We check for normality

edu_planned > 0 (FILTER)		Kolmogorov-Smirnov[a] Statistic	df	Sig.	Shapiro-Wilk Statistic	df	Sig.
Concept C Friction Rank	Not Selected	,315	9	,010	,861	9	,099
	Selected	,173	24	,062	,916	24	,048
Concept C Holding Force Rank	Not Selected	,224	9	,200*	,897	9	,233
	Selected	,165	24	,092	,911	24	,038
Concept C Disengaging Force Rank	Not Selected	,305	9	,016	,799	9	,020
	Selected	,197	24	,016	,831	24	,001
Concept C Stability Rank	Not Selected	,210	9	,200*	,908	9	,300
	Selected	,189	24	,026	,916	24	,047
Concept C Complexity Rank	Not Selected	,135	9	,200*	,950	9	,686
	Selected	,151	24	,164	,956	24	,363

Descriptive statistics:

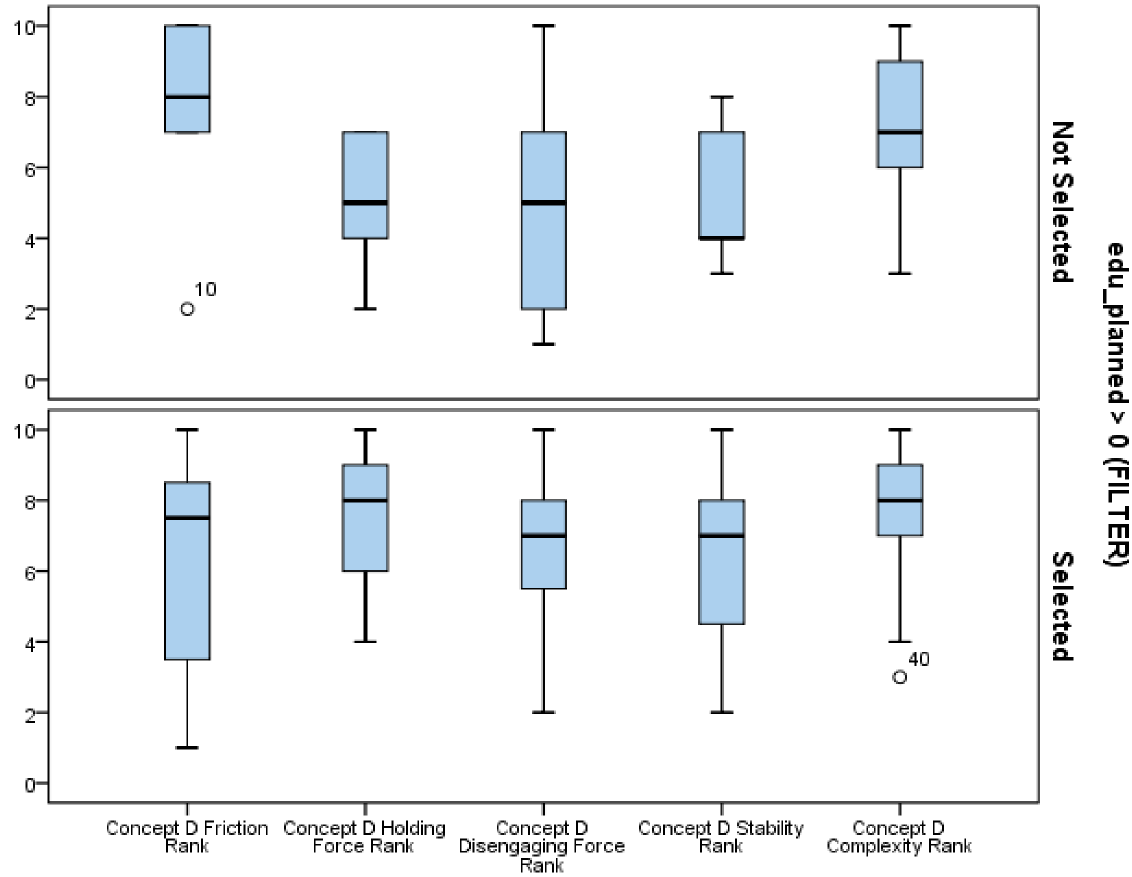
edu_planned > 0 (FILTER)		N	Mean	Std. Deviation	Std. Error Mean
Concept C Friction Rank	Not Selected	9	3,22	2,386	,795
	Selected	24	4,21	2,702	,552
Concept C Holding Force Rank	Not Selected	9	5,00	2,291	,764
	Selected	24	4,42	1,932	,394
Concept C Disengaging Force Rank	Not Selected	9	4,00	2,828	,943
	Selected	24	3,00	1,934	,395
Concept C Stability Rank	Not Selected	9	4,78	2,048	,683
	Selected	24	3,50	1,319	,269
Concept C Complexity Rank	Not Selected	9	4,78	2,048	,683
	Selected	24	5,13	2,232	,456

Independent samples t-test:

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Concept C Friction Rank	Equal variances assumed	1,460	,236	-,961	31	,344	-,986	1,026	-3,078	1,106
	Equal variances not assumed			-1,019	16,238	,323	-,986	,968	-3,036	1,063
Concept C Holding Force Rank	Equal variances assumed	1,439	,239	,735	31	,468	,583	,794	-1,035	2,202
	Equal variances not assumed			,679	12,524	,510	,583	,860	-1,281	2,447
Concept C Disengaging Force Rank	Equal variances assumed	4,460	,043	1,163	31	,254	1,000	,860	-,754	2,754
	Equal variances not assumed			,978	10,933	,349	1,000	1,022	-1,251	3,251
Concept C Stability Rank	Equal variances assumed	2,971	,095	2,122	31	,042	1,278	,602	,050	2,506
	Equal variances not assumed			1,741	10,592	,111	1,278	,734	-,345	2,901
Concept C Complexity Rank	Equal variances assumed	,234	,632	-,406	31	,687	-,347	,855	-2,090	1,396
	Equal variances not assumed			-,423	15,637	,678	-,347	,821	-2,091	1,396

14 STUDENT vs. PRACTITIONER: Rankings of Concept D

We produce boxplot for the distribution, to examine outliers.



We check for normality

edu_planned > 0 (FILTER)		Kolmogorov-Smirnov[a] Statistic	Kolmogorov-Smirnov[a] df	Kolmogorov-Smirnov[a] Sig.	Shapiro-Wilk Statistic	Shapiro-Wilk df	Shapiro-Wilk Sig.
Concept D Friction Rank	Not Selected	,239	9	,147	,774	9	,010
	Selected	,203	24	,012	,897	24	,018
Concept D Holding Force Rank	Not Selected	,191	9	,200*	,902	9	,263
	Selected	,178	24	,047	,913	24	,041
Concept D Disengaging Force Rank	Not Selected	,171	9	,200*	,914	9	,343
	Selected	,271	24	,000	,891	24	,014
Concept D Stability Rank	Not Selected	,310	9	,013	,842	9	,060
	Selected	,186	24	,031	,921	24	,060
Concept D Complexity Rank	Not Selected	,122	9	,200*	,939	9	,569
	Selected	,211	24	,007	,878	24	,008

Descriptive statistics:

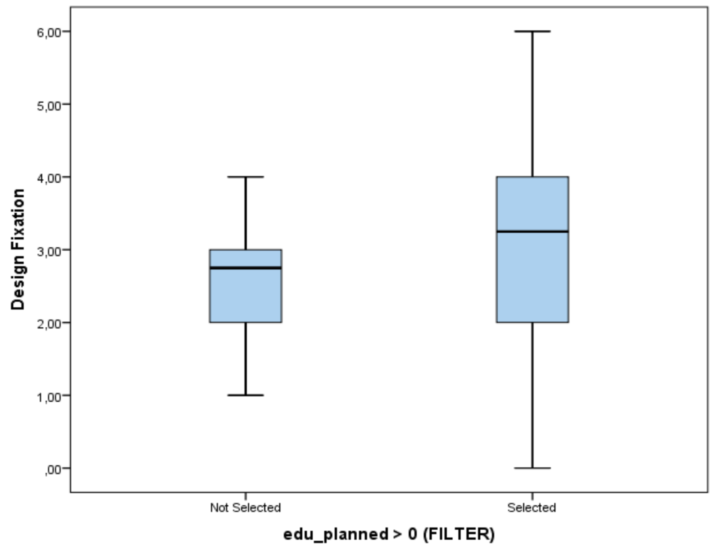
edu_planned > 0 (FILTER)		N	Mean	Std. Deviation	Std. Error Mean
Concept D Friction Rank	Not Selected	9	8,00	2,598	,866
	Selected	24	6,42	2,977	,608
Concept D Holding Force Rank	Not Selected	9	5,00	1,871	,624
	Selected	24	7,54	1,911	,390
Concept D Disengaging Force Rank	Not Selected	9	5,33	3,391	1,130
	Selected	24	6,46	2,043	,417
Concept D Stability Rank	Not Selected	9	5,33	1,936	,645
	Selected	24	6,67	2,200	,449
Concept D Complexity Rank	Not Selected	9	7,00	2,500	,833
	Selected	24	7,75	1,775	,362

Independent samples t-test:

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Concept D Friction Rank	Equal variances assumed	2,019	,165	1,405	31	,170	1,583	1,127	-,716	3,882
	Equal variances not assumed			1,497	16,431	,153	1,583	1,058	-,655	3,821
Concept D Holding Force Rank	Equal variances assumed	,029	,866	-3,422	31	,002	-2,542	,743	-4,057	-1,027
	Equal variances not assumed			-3,456	14,699	,004	-2,542	,736	-4,112	-,971
Concept D Disengaging Force Rank	Equal variances assumed	5,493	,026	-1,169	31	,251	-1,125	,962	-3,088	,838
	Equal variances not assumed			-,934	10,259	,372	-1,125	1,205	-3,800	1,550
Concept D Stability Rank	Equal variances assumed	,099	,755	-1,598	31	,120	-1,333	,835	-3,035	,369
	Equal variances not assumed			-1,696	16,292	,109	-1,333	,786	-2,998	,331
Concept D Complexity Rank	Equal variances assumed	2,124	,155	-,965	31	,342	-,750	,777	-2,335	,835
	Equal variances not assumed			-,825	11,173	,426	-,750	,909	-2,746	1,246

15 STUDENT vs. PRACTITIONER: Design Fixation

We produce boxplot for the distribution, to examine outliers.



We check for normality

edu_planned > 0 (FILTER)		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
Design Fixation	Not Selected	,142	9	,200*	,944	9	,621
	Selected	,133	24	,200*	,956	24	,355

Descriptive statistics:

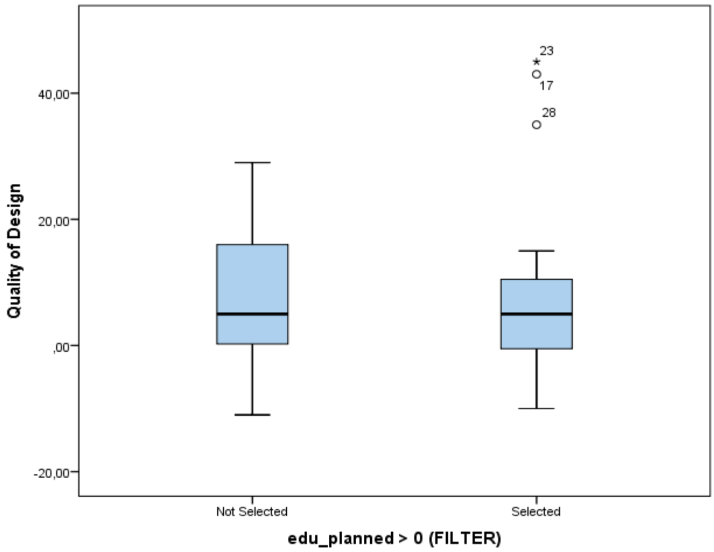
edu_planned > 0 (FILTER)		N	Mean	Std. Deviation	Std. Error Mean
Design Fixation	Not Selected	9	2,6481	,96535	,32178
	Selected	24	3,1458	1,70981	,34901

Independent samples t-test:

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Design Fixation	Equal variances assumed	3,101	,088	-,820	31	,418	-,49769	,60673	-1,73512	,73975
	Equal variances not assumed			-1,048	25,580	,304	-,49769	,47472	-1,47426	,47889

16 STUDENT vs. PRACTITIONER: Quality of Design

We produce boxplot for the distribution, to examine outliers.



We check for normality

edu_planned > 0 (FILTER)		Kolmogorov-Smirnov[a] Statistic	df	Sig.	Shapiro-Wilk Statistic	df	Sig.
Quality of Design	Not Selected	,153	9	,200*	,971	9	,903
	Selected	,252	24	,000	,807	24	,000

Descriptive statistics:

edu_planned > 0 (FILTER)		N	Mean	Std. Deviation	Std. Error Mean
Quality of Design	Not Selected	9	6,8148	12,85339	4,28446
	Selected	24	7,5833	14,44003	2,94756

Independent samples t-test:

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference Lower	Upper
Quality of Design	Equal variances assumed	,001	,981	-,140	31	,890	-,76852	5,49081	-11,96710	10,43007
	Equal variances not assumed			-,148	16,110	,884	-,76852	5,20046	-11,78690	10,24986

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Appendix D

Example on Removing Outliers in SPSS

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Removing outlier data from SPSS (Example)

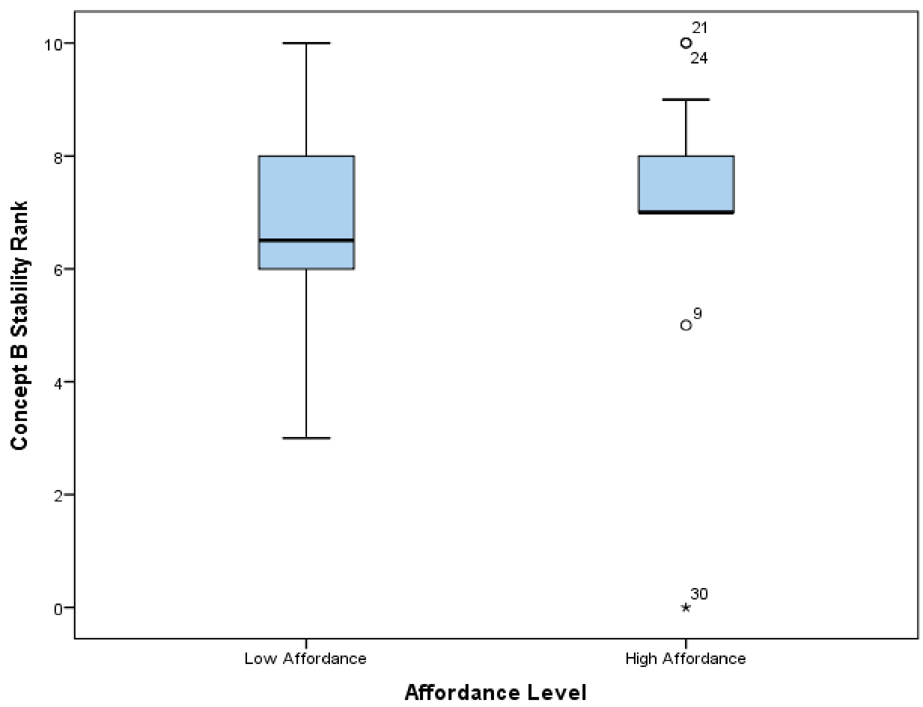
To see whether removing outliers is a good option or not, we have decided to include this example as an appendix in out thesis. Here, we want to show the effect of using/discarding the outliers in a statistical test, and therefore reason why we have chosen to keep all outliers in our tests. Generally speaking, we can divide outliers into three main categories, these being;

- Data entry errors
- Measurement errors
- Genuinely unusual values

In the example provided here, we have no way of investigating that the participants have entered the data wrongly. However, we have checked (and double checked) that the data we are analyzing is indeed the same as provided by the participants. Hence, we assume that all outliers in the dataset are genuinely unusual values.

Test with outliers

In this example, we are using the data from the participants ranking the stability of ‘Concept B’. In this data, the distribution is as follows:



Here, we can see outliers apparent in the high affordance condition – namely participant numbers 9, 21, 24 and 30. 9, 21 and 24 are mild outliers, and 30 is an extreme outlier.

Testing for normality, we see that the high affordance distribution violates the assumption of non-normality when the outliers are included:

Affordance Level		Kolmogorov-Smirnov[a] Statistic	df	Sig.	Shapiro-Wilk Statistic	df	Sig.
Concept B Stability Rank	Low Affordance	,207	16	,065	,926	16	,212
	High Affordance	,331	17	,000	,762	17	,001

As shown in the Results section of our thesis, performing a Student T-test on this dataset provides the following results:

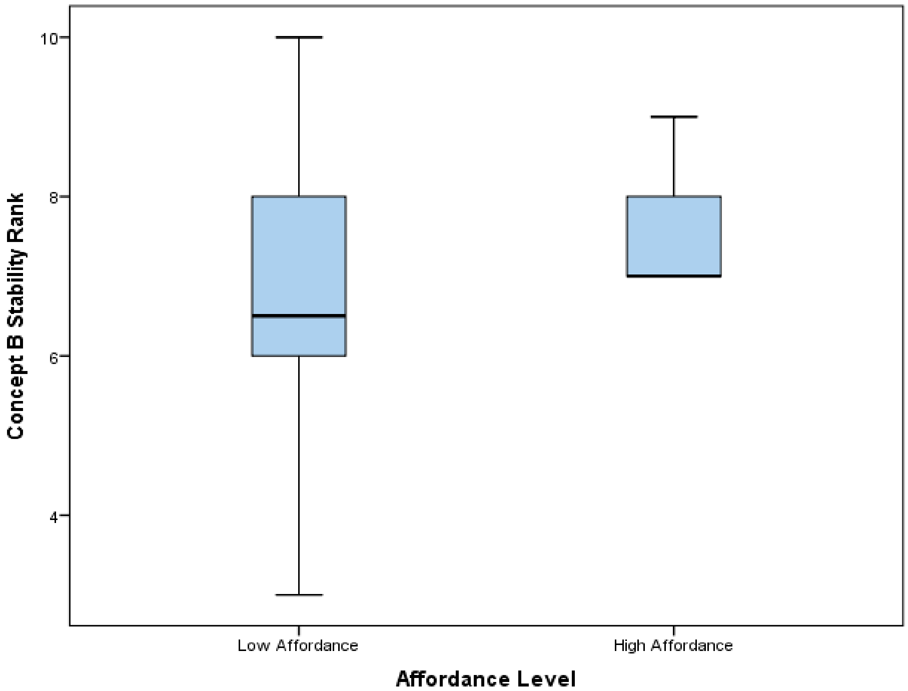
Affordance Level		N	Mean	Std. Deviation	Std. Error Mean
Concept B Stability Rank	Low Affordance	16	6,69	1,778	,445
	High Affordance	17	7,29	2,257	,547

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference Lower	95% Confidence Interval of the Difference Upper
Concept B Stability Rank	Equal variances assumed	,018	,894	-,854	31	,400	-,607	,710	-2,056	,842
	Equal variances not assumed			-,860	30,098	,397	-,607	,705	-2,047	,834

This result is non-significant for both ‘Levene’s test for Equality of Variances’ and ‘t-test for Equality of Means’ (highlighted in grey).

Test without outliers

If we remove the outliers from the dataset, we get the following distribution:



As we can see, all outliers have been removed. Further analyzing the normality gives us:

Affordance Level		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
Concept B Stability Rank	Low Affordance	,207	16	,065	,926	16	,212
	High Affordance	,327	13	,000	,756	13	,002

Note that the high affordance condition still violates the assumption of non-normality.

However, while performing a Student T-test on this dataset provides the following results:

Affordance Level		N	Mean	Std. Deviation	Std. Error Mean
Concept B Stability Rank	Low Affordance	16	6,69	1,778	,445
	High Affordance	13	7,62	,768	,213

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Concept B Stability Rank	Equal variances assumed	7,384	,011	-1,749	27	,092	-,928	,531	-2,017	,161
	Equal variances not assumed			-1,882	21,275	,074	-,928	,493	-1,952	,097

Conclusion

In this appendix, we have shown that while removing the outliers may be preferable to get 'cleaner' statistical data, we have also shown that we dilute the results. If the outliers are indeed genuinely unusual values (and not due to errors), we argue that including the outliers in our analyses is the right thing to do, as the removal of outliers may produce misleading (and potentially flawed) results.

Appendix E

MATLAB Post- and Pre-Processing

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```matlab
%% Pre-processing script: matlab pre-processing for apriori algorithm
% Matlab script for preprocessing experiment data for applying the apriori
% algorithm to identify data patterns.

% Created by: Andreas Lyder Pedersen
% Date: 12.04.2016

%% Needs
% A testdata output file
% An excel input file

%% 1) Read data from excel
% xlsread returns a matrix of numbers in the file, sheet and range
specified
oldNum = xlsread('ExcelTest', 'Sheet2', 'D3:AD35'); % Specifies read file
name, sheet, and cell range

%% 2) Create an array to identify attribute
% Create an array of strings to match the positioning of the variables in
% the excel sheet.

catArray = {'Gender', 'Affordance', ...
    'IntFricWeight', 'IntFricConA', 'IntFricConB', 'IntFricConC',
'IntFricConD', ...
    'HoldForceWeight', 'HoldForceConA', 'HoldForceConB', 'HoldForceConC',
'HoldForceConD', ...
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'DisEngForConD', ...
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'StabilityOveAffAvgConD', ...
```

```
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'ComplexitOveAffAvgConB', 'ComplexitOveAffAvgConC',
'ComplexitOveAffAvgConD', ...
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'IntFricAllAvgStdConB', 'IntFricAllAvgStdConC', 'IntFricAllAvgStdConD', ...
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'StabilityAllAvgStdConB', 'StabilityAllAvgStdConC',
'StabilityAllAvgStdConD', ...
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'ComplexitAllAvgStdConB', 'ComplexitAllAvgStdConC',
'ComplexitAllAvgStdConD', ...
%    'IntFricAffAvgStdWeight', 'IntFricAffAvgStdConA',
'IntFricAffAvgStdConB', 'IntFricAffAvgStdConC', 'IntFricAffAvgStdConD', ...
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'StabilityDiffAvgAAConB', 'StabilityDiffAvgAAConC',
'StabilityDiffAvgAAConD', ...
%    'ComplexitDiffAvgAAWeight', 'ComplexitDiffAvgAAConA',
'ComplexitDiffAvgAAConB', 'ComplexitDiffAvgAAConC',
'ComplexitDiffAvgAAConD'};

%% 3) Regroups the data matrix
% Outsources regrouping of data to a function
% The functions regroupData1 and regroupData2 have slightly different
% grouping.

%num = regroupData1(oldNum); % Regroups, see description of regroupData1.m
%num = regroupData2(oldNum); % Regroups, see description of regroupData2.m
%Lol
num = oldNum; % No regrouping

%% 4) Endzone
% Opens the testdata file
fileID = fopen('testdata','w');

% Retrieves the size of the data matrix.
```

```
% length(1) is height, length(2) is width.
length = size(num);

for i = 1:length(1)
    for j = 1:length(2)
        tempString = char(strcat(catArray(j),num2str(num(i,j))));
        if j == length(2) && i ~= length(1)
            fprintf(fileID, tempString);
            fprintf(fileID, ' \n');
        else
            fprintf(fileID, tempString);
            fprintf(fileID, ' ');
        end
    end
end

fclose(fileID);
```

```matlab
%% Filter Output 1
% Matlab post-processing script for applying the apriori data mining
% algorithm to experiment data.

% Will read patterns from an excel file, filter the patterns by a
% searchable phrase, and write the valid patterns to an excel file.

% Created by: Andreas Lyder Pedersen
% Date: 12.04.2016

%% Indexing
keyPhrases = ['Affordance']; % Adjust according to searchable phrase
ExcelCellRange = 'A1:F742'; % Adjust according to excel cell range

%% 1) Reads from excel
% Uses [numericMatrix, textArray] =  xlsread(filename, sheetname,
cellRange)
[oldNum,oldTxt] = xlsread('ExcelTest', 'FilterInput', ExcelCellRange);

%% Determine length of the array

% length(1) is height, length(2) is width.
MatLength = size(oldTxt);
%% Search through the matrix for keywords, save index to vector

KeyVector = [];
KeyVectorCounter = 1;

for i = 1:MatLength(1)
    for j = 1:MatLength(2)
        if ~isempty(strfind(char(oldTxt(i,j)), keyPhrases));
            KeyVector(KeyVectorCounter) = i;
            KeyVectorCounter = KeyVectorCounter + 1;
            break
        end
    end
end

%% Save to excel
filename = 'ExcelTest.xlsx';
xlswrite(filename,oldNum(KeyVector),'FilterOutput','A1');
xlswrite(filename,oldTxt(KeyVector,:),'FilterOutput','B1');
```

Appendix F

Python Code: Apriori Datamining Algorithm

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CREDIT TO HÅKON KAUREL FOR IMPLEMENTATION.

```
import itertools as it
import sys


def contains_subset(_set, collection):
    possible_subsets = it.combinations(_set, len(_set)-1)
    for subset in possible_subsets:
        if frozenset(subset) in collection:
            return True
    return False


def generate_combinations(items, combination_len, prune_sets):
    raw_combinations = [frozenset(c) for c in it.combinations(items, combination_len)]
    prune_sets = frozenset(prune_sets)
    combinations = [c for c in raw_combinations if not contains_subset(c, prune_sets)]
    print("PRUNED COMBINATIONS: " + str(len(raw_combinations)-len(combinations)))
    return combinations



def generate_occurrences(dataset, combinations):
    occurrences = {}
    for combination in combinations:
        occurrences[combination] = 0
        for transaction in dataset:
            if combination.issubset(transaction):
                occurrences[combination]+=1

    return occurrences


def generate_items(occurrences, threshold):
    items = frozenset()
    prune_sets = []
```

```
    for key in occurrences.keys():
        if occurrences[key] >= threshold:
            items = items.union(frozenset([item for item in key]))
        else:
            prune_sets.append(frozenset(key))

    return items, prune_sets

def load_data_from_file(filename):
    data = []
    with open(filename) as _file:
        for line in _file:
            data.append(line.rstrip().split(" "))
    return data



def main():
    threshold = 14
    depth = 200

    items = frozenset([])
    prune_sets = []
    data = load_data_from_file(sys.argv[1])

    result_occurrences = []
    for transaction in data:
        items = items.union(transaction)

    for i in range(1, depth+1):
        print("ITERATION #" + str(i) + " STARTED!")
```

```
        print("ITEMS LEFT: "+ str(len(items)))
        print("GENERATING COMBINATIONS")
        combinations = generate_combinations(items, i, prune_sets)
        print("GENERATING OCCURRENCES")
        occurrences = generate_occurrences(data, combinations)
        print("GENERATING ITEMS")
        items, prune_sets = generate_items(occurrences, threshold)
        result_occurrences.append(occurrences)
        print("ITERATION #" + str(i) + " DONE!")

        if len(items) == 0:
            print("RAN OUT OF ITEMS")
            break

    for i in range(len(result_occurrences)):
        for key in result_occurrences[i].keys():
            if result_occurrences[i][key]>=threshold:
                line = str(result_occurrences[i][key])
                for item in key:
                    line += ","+str(item)
                print(line)
if __name__=="__main__":
    main()
```

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Appendix G

Apriori Datamining Algorithm Results

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SELECTED APRIORI RESULTS BY THRESHOLD AND PATTERN LENGTH

a. Threshold 9; Pattern length 2

Occurences	Attribute 1	Attribute 2
13	Male	Holding Force Weighting: 3
12	Male	Complexity Weighting: -2
10	Male	Complexity Concept A: 3
10	Male	Stability Weighting: 2
9	Male	Stability Weighting: 3
9	High Affordance	Holding Force Weighting: 3

b. Threshold 4; Pattern length 5

Occurences	Attribute 1	Attribute 2	Attribute 3	Attribute 4	Attribute 5
4	Male	Complexity Weighting: -2	Stability Weighting: 3	Holding Force Concept C: 6	Holding Force Weighting: 2
4	Male	Complexity Weighting: -2	Interface Friction Concept A: 3	Complexity Concept A: 3	Disengaging Force Weighting: -2
4	Male	High Affordance	Interface Friction Concept A: 3	Complexity Concept A: 3	Disengaging Force Concept A: 3
4	Male	High Affordance	Interface Friction Weighting: -2	Disengaging Force Concept C: 2	Stability Weighting: 2

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Appendix H

Risk Assessment

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Dato: 15.01.2016

Enhet: Department of Engineering Design and Materials

Linjeleder: Torgeir Welo

Deltakere ved kartleggingen (m/ funksjon)**:** Achim Gerstenberg, Stud.ass./ Martin Steinert, veileder/ Andreas L. Pedersen, student / Jørgen A. B. Erichsen, student. *(Ansv. veileder, student, evt. medveiledere, evt. andre m. kompetanse)*

Kort beskrivelse av hovedaktivitet/hovedprosess: Masteroppgave student Andreas L. Pedersen og Jørgen A. B. Erichsen. Using Prototypes to Leverage Tacit Knowledge – Experimenting with Tacit Knowledge in Product Development

Er oppgaven rent teoretisk? (JA/NEI)**: NEI** *«JA» betyr at veileder innestår for at oppgaven ikke inneholder noen aktiviteter som krever risikovurdering. Dersom «JA»: Beskriv kort aktiviteteten i kartleggingskjemaet under. Risikovurdering trenger ikke å fylles ut.*

Signaturer: *Ansvarlig veileder: Martin Steinert* *Student: Andreas L. Pedersen og Jørgen A. B. Ericshen*

ID nr.	Aktivitet/prosess	Ansvarlig	Eksisterende dokumentasjon	Eksisterende sikringstiltak	Lov, forskrift o.l.	Kommentar
1	Bruk av TrollLABS workshop.	ALP & JABE	Romkort	Romkort		
1a	Bruk av roterende maskineri	ALP & JABE	Maskinens brukermanual, Maskinkort	Maskinkort, Sikringskabinett	Ukjent	
1b	Bruk av laserkutter	ALP & JABE	Maskinens brukermanual, Maskinkort	Maskinkort	Ukjent	
1c	Bruk av 3D printer	ALP & JABE	Maskinens brukermanual, Maskinkort	Maskinkort	Ukjent	
1d	Bruk av skjæreverktøy	ALP & JABE	Ukjent			

1e	Bruk av samenføynigsmidler (lim og lignende.)	ALP & JABE	Produktets brukermanual og datablad	Datablad	Ukjent	
2	Tilstedeværelse ved arbeid utført av andre.	Andre	Andres HMSRV2601	Andres HMSRV2601	Prosessavhengig	

ID nr	Aktivitet fra kartleggings-skjemaet	Mulig uønsket hendelse/ belastning	Vurdering av sannsyn-lighet	Vurdering av konsekvens:				Risiko-Verdi (menn-eske)	Kommentarer/status Forslag til tiltak
			(1-5)	Menneske (A-E)	Ytre miljø (A-E)	Øk/ materiell (A-E)	Om-dømme (A-E)		
1	Bruk av Trolllabs workshop.								
1a-i	Bruk av roterende maskineri	Stor kuttskade	2	D	A	A	D	2D	Sørg for at roterende deler tilstrekkelig sikret/dekket. Vær nøye med opplæring i bruk av maskineri.
1a-ii		Liten kuttskade	3	B	A	A	A	3B	Vær nøye med opplæring i bruk av maskineri. Ikke ha løse klær/tilbehør på kroppen.
1a-iii		Klemskade	2	D	A	A	C	2D	Vær nøye med opplæring i bruk av maskineri. Ikke ha løse klær/tilbehør på kroppen.
1a-iv		Flygende spon/gjenstander	3	C	A	A	B	3C	Bruk øyevern og tildekk hurtig roterende deler (Fres og lignende.)
1a-v		Feil bruk-> ødelagt utstyr	3	A	A	C	A	3C	Vær nøye med opplæring i bruk av maskineri
1b-i	Bruk av laserkutter	Klemskade	2	D	A	A	C	2D	Vær nøye med opplæring i bruk av maskineri. Ikke ha løse klær/tilbehør på kroppen.
1b-ii		Brannskade	3	B	A	A	A	3B	Vær nøye med opplæring i bruk av maskineri. Bruk hansker ved håndtering av varme materialer.

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1b-iii		Øyeskade-laser	2	D	A	A	C	2D	Bruk øyevern! Skru av laser når maskinen ved oppsett.
1b-iv		Brann	2	B	A	D	C	2B	Vær nøye med opplæring i bruk av maskin. Ha slukkeutstur tilgjengelig
1c-i	Bruk av 3D-printer	Brannskade	3	B	A	A	A	3B	Vær nøye med opplæring i bruk av maskin.
1c-ii		Innhalering av plast/ printemateriale	5	A	A	A	A	5A	Bruk åndedretsvern/ vernebriller
1c-iii		Feil bruk-> ødelagt maskineri	3	A	A	C	A	3A	Vær nøye med opplæring i bruk av maskin.
1d-i	Bruk av skjæreverktøy	Stor kuttskade	2	D	A	A	D	2D	Bruk skapre verktøy og riktig skjæreunderlag
1d-ii		Liten kuttskade	3	B	A	A	A	3B	Bruk skapre verktøy og riktig skjæreunderlag
1e-i	Bruk av samenføynigsmidler (lim og lignende.)	Eksponering på øyet	2	D	A	A	B	2D	Bruk øyevern, ha datablad tilgjengelig
1e-ii		Eksponering hud	4	A	A	A	A	4A	Bruk hansker, ha datablad tilgjengelig
1e-iii		Eksponering åndedrett	4	A	A	A	A	4A	Bruk åndedretsvært/ god ventilasjon. Ha datablad tilgjengelig.
1e-iv		Søl	4	A	B	A	A	4A	Ha papir/ rengjøringsmateriell tilgjengelig. Ha datablad

									tilgjengelig.
2	Tilstedeværelse ved arbeid utført av andre.	Se andres risikovurdering om sikkerhet betviles.	3	C	C	C	C	3C	Hold et øye med hva som foregår rundt deg.
3-i	Eksperimentelt arbeid	Vann-drukning	1E	A	A	A	D	1E	Bruk redingsvest i båt og lignende.
3-ii		Elektrisitet- strøm	3	B	A	A	A	3V	Typisk lite energi involvert. Bruk isolerte verkøty

Sannsynlighet vurderes etter følgende kriterier:

Svært liten 1	Liten 2	Middels 3	Stor 4	Svært stor 5
1 gang pr 50 år eller sjeldnere	1 gang pr 10 år eller sjeldnere	1 gang pr år eller sjeldnere	1 gang pr måned eller sjeldnere	Skjer ukentlig

Konsekvens vurderes etter følgende kriterier:

Gradering	Menneske	Ytre miljø Vann, jord og luft	Øk/materiell	Omdømme
E **Svært Alvorlig**	Død	Svært langvarig og ikke reversibel skade	Drifts- eller aktivitetsstans >1 år.	Troverdighet og respekt betydelig og varig svekket
D **Alvorlig**	Alvorlig personskade. Mulig uførhet.	Langvarig skade. Lang restitusjonstid	Driftsstans > ½ år Aktivitetsstans i opp til 1 år	Troverdighet og respekt betydelig svekket
C **Moderat**	Alvorlig personskade.	Mindre skade og lang restitusjonstid	Drifts- eller aktivitetsstans < 1 mnd	Troverdighet og respekt svekket
B **Liten**	Skade som krever medisinsk behandling	Mindre skade og kort restitusjonstid	Drifts- eller aktivitetsstans < 1uke	Negativ påvirkning på troverdighet og respekt
A **Svært liten**	Skade som krever førstehjelp	Ubetydelig skade og kort restitusjonstid	Drifts- eller aktivitetsstans < 1dag	Liten påvirkning på troverdighet og respekt

Risikoverdi = Sannsynlighet x Konsekvens
Beregn risikoverdi for Menneske. Enheten vurderer selv om de i tillegg vil beregne risikoverdi for Ytre miljø, Økonomi/materiell og Omdømme. I så fall beregnes disse hver for seg.

Til kolonnen "Kommentarer/status, forslag til forebyggende og korrigerende tiltak":
Tiltak kan påvirke både sannsynlighet og konsekvens. Prioriter tiltak som kan forhindre at hendelsen inntreffer, dvs. sannsynlighetsreduserende tiltak foran skjerpet beredskap, dvs. konsekvensreduserende tiltak.

MATRISE FOR RISIKOVURDERINGER ved NTNU

KONSEKVENS						
	Svært alvorlig	E1	E2	E3	E4	E5
	Alvorlig	D1	D2	D3	D4	D5
	Moderat	C1	C2	C3	C4	C5
	Liten	B1	B2	B3	B4	B5
	Svært liten	A1	A2	A3	A4	A5
		Svært liten	Liten	Middels	Stor	Svært stor
		SANNSYNLIGHET				

Prinsipp over akseptkriterium. Forklaring av fargene som er brukt i risikomatrisen.

Farge	Beskrivelse
Rød	Uakseptabel risiko. Tiltak skal gjennomføres for å redusere risikoen.
Gul	Vurderingsområde. Tiltak skal vurderes.
Grønn	Akseptabel risiko. Tiltak kan vurderes ut fra andre hensyn.