# RAW SHAPING FORM FINDING

## SEVEN TACIT TANGIBLE INTERACTIVE DESIGN EXPERIMENTS

ANALYSIS AND EVALUATION FOR DEVELOPMENT OF HYBRID DESIGN TOOLS
FOR DESIGN AND ENGINEERING PROCESSES

UNIVERSITY OF TWENTE.

rawshaping
technology

Master thesis | Olaf Grevenstuk | May 2018 | University of Twente | Industrial Design Engineering | Faculty of Engineering Technology

Master thesis

Title: **Raw Shaping Form Finding (RSFF) - Seven tacit tangible interactive design experiments**

Analysis and evaluation for development of hybrid design tools for design and engineering processes

UNIVERSITY OF TWENTE.


| | |
|---|---|
| STUDENT | O. GREVENSTUK |
| MASTER TRACK | INDUSTRIAL DESIGN ENGINEERING |
| | EMERGING TECHNOLOGY DESIGN |
| UNIVERSITY | UNIVERSITY OF TWENTE |
| THESIS NO. | DPM1517 |
| DATE | May 2018 |
| | RAWSHAPING TECHNOLOGY |
| COMMITTEE: | |
| CHAIRMAN | PROF. DR. IR. A. DE BOER |
| MENTOR | DR. ING. R.E. WENDRICH |
| MEMBER | DR. IR. D. LUTTERS |

# PREFACE

All education is a process of learning, trial and error, and refinement. For this Master assignment the process was no different. Without the help of some people in particular, this thesis would not have turned out as the document that lies in front of you, dear reader.

For that I would sincerely like to thank;

Dr. Ing. Robert E. Wendrich as mentor, as fellow experimenter / tinkerer and as good friend. The many hours with the RST team research and experiments, the RST international exhibition team efforts and the many social hours of open minded discussions, good food and hot or cold beverages. In the last 10+ years we learned to appreciate each other's qualities and successfully completed many RST prototype problems and system builds. For all those years and still the many available years ahead, I would like to say again, thank you friend!

Prof. Dr. Ir. A. de Boer for the kind words during email communication and progress meetings. Furthermore, allowing me to conduct this research.

Dr. Ir. D. Lutters for participation in the assessment committee.

The RAWSHAPING TECHNOLOGY (RST) team for their friendly input and feedback on various RST research challenges. It was a pleasure to work with the team and see every one of them always aim for the best possible solution. Not because they had to, but because they wanted to. Keep up the good work!

Friends and family for their support and believe in a successful completion of my Master assignment.

And finally, all the participants (BSc. and MSc. students, IDE employees and external expert designers) that attended the seven experiments explained in this Master thesis.

# SUMMARY

A main task of industrial designers is the shaping and transformations of ideas or fuzzy notions into abstract or materialized equivalents. These sketches, models, or other representations can be described as the sum of 3-D form and 2-D shape aspects, aesthetics, intuitive qualities, tacit-knowing, as well as technical and sustainable functionalities. The designer must understand the elements involved in this synthesis of form-giving and design. Successful designers compose these characteristics carefully and join them together to form and shape artefacts into a harmonious and balanced whole, while simultaneously manoeuvring within implicit and explicit mechanical and functional aspects (Wendrich, 2009).

With the emergence of 3-D computational design, the industrial design and engineering process shifted from traditional analogue physical representations of ideas or artefacts to digital virtual realities. This shift is creating pre-dominance of digital design over the idiosyncrasies of analogue craftsmanship of the designer. Loss of control, immediacy, manual dexterity and skills due to constraint in electronic interfaces (i.e. windows-keyboard-mouse-monitor-pointer) and programmer's directions. Subsequently, this gave way to alienation of the physical material world and created voids in the support of design processes (Wendrich, 2010).

In this report, we follow two main research directions in our attempt to bridge this gap. Firstly, we execute an empirical user-study in combination with seven tacit-tangible design task experiments. We aim to measure the effectiveness (i.e. qualitative), performance, and other qualities of various shaping and representation techniques. Secondly, we show the preliminary design and build of hybrid design tool prototypes (RSFF-HDT) that targets to bring back the tacit-tangible elements of design and/or engineering processes integrated in CAD-systems.

We investigate and explore possible distinctions between the analogue and digital representation tools, explain the seven laboratory experiments, and analysis and evaluate testing results. Furthermore, correlation between empirical research and educational embedding in conjunction with the creative opportunities that emerge from embedment of hybrid design tools (HDT’s) and/or HDT-environments (HDTE’s) is described.

# SAMENVATTING

Een belangrijke taak voor ontwerpers en ingenieurs is het vormgeven, ontwerpen, specificeren en vertalen van ideeën of moeilijk definieerbare problemen naar abstracte, concrete oplossingen en/of modellen. Deze schetsen, modellen, prototypen of andere representaties zijn, naast de zorgvuldige afwegingen en het itereren van technische mogelijkheden een synthese tussen tweedimensionale en driedimensionale vormaspecten, esthetiek, intuïtieve kwaliteiten, en praktische ervaring. Dit is inclusief het bepalen van de technische- en duurzame functionaliteiten. De ontwerper zal binnen deze synthese van vormgeven en ontwerpen zoveel mogelijk proberen om alle onderdelen en delen technisch te vertalen en te integreren. Succesvolle ontwerpers of ingenieurs, zijn in staat om alle deze eigenschappen, specificaties, wensen en eisen harmonieus en uitgebalanceerd samen te voegen (vormgeving, ontwerpen), terwijl ze voortdurend rekening houden met impliciete en expliciete mechanische en functionele aspecten gedurende het ontwerpproces (Wendrich, 2009).

Met de introductie van computergestuurde 3-D CAD systemen, veranderde het ontwerp- en technisch-ontwerp proces van traditionele analoge ideeontwikkeling en representatie in het vastleggen en visualiseren van driedimensionale informatie en data binnen een digitale virtuele realiteit. Door de schijnbare efficiëntie, gebruiksgemak en verhoogde effectiviteit van CAD omgevingen werd deze nieuwe techniek al vrij snel geadapteerd en dominant in gebruik binnen de ontwerp- en techniekdomeinen. De analoge en impliciete kennis, expliciete vaardigheden en kenmerkende vakmanschap van ontwerpers en ingenieurs verdween hierdoor haast automatisch. Vooral het verlies van direct inzicht, handigheid (heuristiek), controle- en toepassing van kennis gedurende een ontwerpproces kwam hierdoor ernstig onder druk. De CAD-programma's leiden vaak naar een beperking van het menselijk inzicht. De handelingen worden veelal gestuurd en tegelijkertijd beperkt door voorgeprogrammeerde oplossingsrichtingen binnen deze digitale systemen. Het gevolg is dat er een 'nieuwe' generatie ontwerpers en ingenieurs ontstaat die vaak geen enkele affiniteit hebben met de fysiek-tastbare en intuïtieve wereld en vervreemd zijn geraakt van deze realiteit binnen de ontwerpprocessen (Wendrich, 2009-2010). Om deze zichtbare 'kloof' te dichten en/of te overbruggen, is er door Wendrich en Tideman in 2004 een onderzoek gestart om de analoge en digitale werelden (hybridisering) dichter bij elkaar te brengen of te laten samenvloeien door specifieke ontwerpgereedschappen en –omgevingen te creëren.

We volgen twee belangrijke onderzoeksrichtingen die in dit rapport worden beschreven en omschreven. Initieel wordt er een empirische gebruikersstudie (kwalitatief onderzoek) uitgevoerd met een diversiteit aan ontwerpers, die allen verschillende kennis- en ervaringsniveaus hebben. Deze studie en experimenten bestaan uit zeven verschillende ontwerp-opstellingen, die variëren tussen het maken van simpele analoge- tot en met het creëren van volledig digitale representaties. De gebruikers (ontwerpers) worden per experiment getest door middel van het uitvoeren van een specifieke ontwerptaak binnen een vooraf vastgestelde tijd. Hierbij meten, vergelijken en observeren we de effectiviteit, prestaties, snelheid, tastbare resultaten en andere aspecten van de zeven verschillende representatietechnieken. In het tweede deel van dit onderzoek, presenteren we de ontwikkeling en ontwerpen van prototypen die leiden tot een mogelijke oplossing van hybride intuïtieve ontwerpgereedschappen en –omgevingen (RSFF-HDT). De specificaties, eisen en wensen van deze prototypen zijn mede gebaseerd op de resultaten, analyses, evaluaties, en bevindingen die voortvloeien uit de zeven laboratoriumexperimenten.

Diverse prototypen worden ontwikkeld, gebouwd, en ingezet om potentiële mogelijkheden, nieuwe oplossingen en eventuele beperkingen van analoge- en digitale representatiehulpmiddelen te onderzoeken, te testen en te verkennen met diverse gebruikers, gebruiksdomeinen, en gebruiksgroepen. Bovendien wordt de directe correlatie tussen educatieve doelstellingen in ontwerponderwijs en empirisch onderzoek beschreven. Dit is in samenhang met de creatieve mogelijkheden die voortkomen uit de doelstelling en oplossingsrichtingen die hybride ontwerptools (HDT's) en/of HDT-omgevingen (HDTE's) bieden.

# LIST OF ABBREVIATIONS

| | |
|---|---|
| 2-D | two dimensional |
| 3-D | three dimensional |
| AER | Automatic Emotion Recognition |
| AM | Additive Manufacturing |
| API | Application Programming Interface |
| CAD | Computer Aided Design |
| CC | Correlation Coefficient |
| CNN | Convolutional Neural Networks |
| COTS | Commercial-Off-The-Shelf |
| CSS3 | Cascading Style Sheets 3 |
| HDT | Hybrid Design Tool |
| HDTE | Hybrid Design Tool Environment |
| HTML5 | Hyper Text Markup Language 5 |
| IA | Interaction |
| IxD | Interaction Design |
| MQ | Mean Quality |
| PCP | Product Creation Process |
| PEP | Product Engineering Process |
| RQ | Ranked Quality |
| RSFF | Rawshaping Formfinding Tool |
| RST | Rawshaping Technology |
| TBC | Tie Break Column |
| UIA | User Interaction |
| VFG | Virtual Formgiving |
| VIA | Video Interaction Analysis |
| WIMP | Windows, Interaction, Menu’s and Pointers |
| X1 | Experiment 1 |
| X2 | Experiment 2 |
| X3 | Experiment 3 |
| X4 | Experiment 4 |
| X5 | Experiment 5 |
| X6 | Experiment 6 |
| X7 | Experiment 7 |

# LIST OF FIGURES

# LIST OF TABLES

# CONTENTS

# CHAPTER 1 - INTRODUCTION

## 1.1 The Rawshaping Formfinding Paradigm (RSFF) and Frame of Mind – Early Phase Research

To start a product creation process (PCP) and/or product engineering process (PEP), one of the first things a designer does is, after initially been documented or briefed, to pick up a pencil and paper and starts to sketch first ideas or impressions. These representations are quick, mostly random thoughts committed to paper and while sketching they start to portray the outlines of possible solutions for a specific design problem or task. Slowly but steady, these sketches become more sure, stable, and subsequently, through iterative steps, ideas become more clear, concise, and structured (Fig. 1-1).

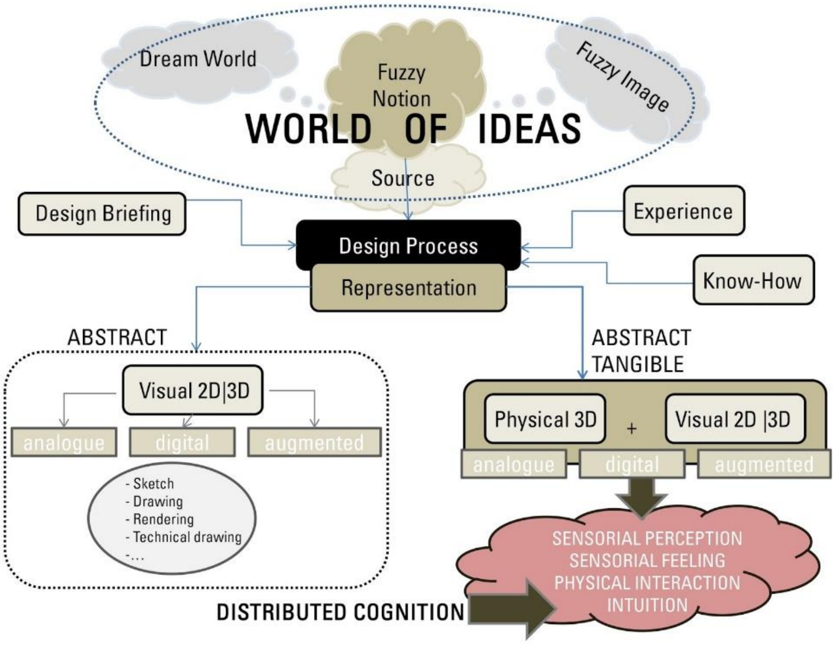



**Fig. 1-1** Human capacity to externalize meta-cognitive abilities (Wendrich, 2013)

Sketching two- or three dimensional, is a way to present and represent ideas and give way to order, plan, and structure within a possible solution space (Fig. 1-1 and 1-2). However, this sketching process is not the only thing a designer and/or engineer uses to convey ideas, fussy notions, or ill-structured thoughts. Another possibility is to process in combination with or separately produce, three-dimensional sketches in reflective material, i.e. paper, cardboard, wood, metal wire, plastics or a formable mass like clay (Fig. 1-2).

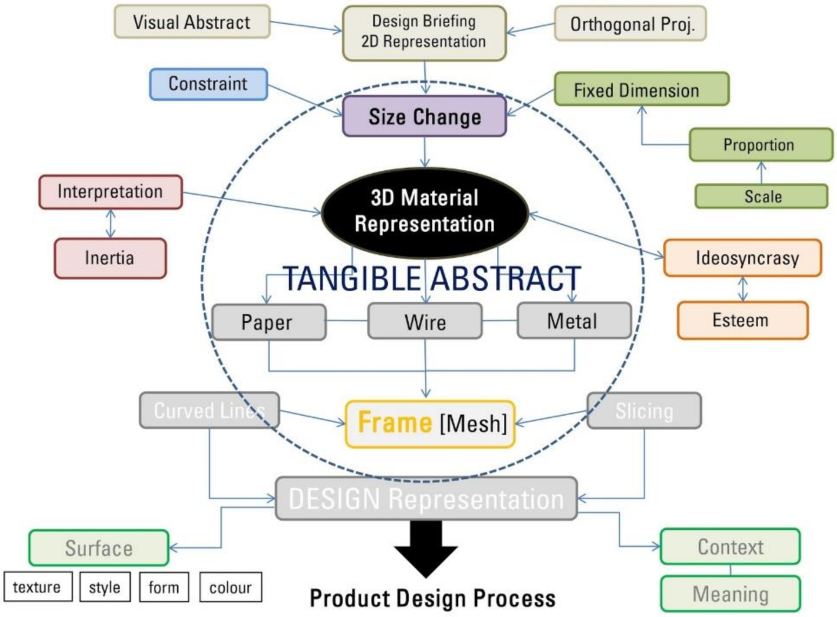



**Fig. 1-2** Product design process by means of 3-D material representation (Wendrich, 2008)

In this way the designer/engineer starts to represent and materialize ideas directly into touch-and-feel semantics and nudges itself into three-dimensional space by making use of the positive-negative connotations derived from ready-made or quick-thumb artefacts (i.e. low-resolution prototypes).

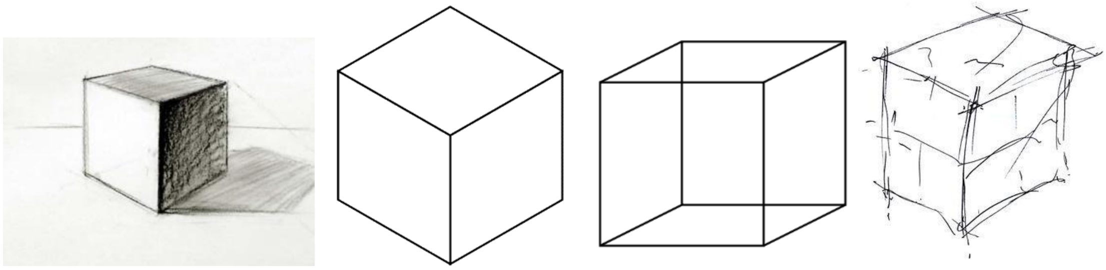


**Fig. 1-3** Various Cube Sketch Representations

In sketching, for example a cube on paper (Fig. 1-3), the feeling of three-dimensions emerge from taking a certain perspective, the placement of lines, adding shadows applying hatching and so forth. The viewer will get some kind of notion of what the design entails without directly fully understanding the scope of the represented object. After all, the represented cube will stay an approximation and most certainly an interpretation of the designer's mind's eye, frame of mind, and inherent skills as indicated and presented in the diagram on page 5 in Fig. 1-6 Left.

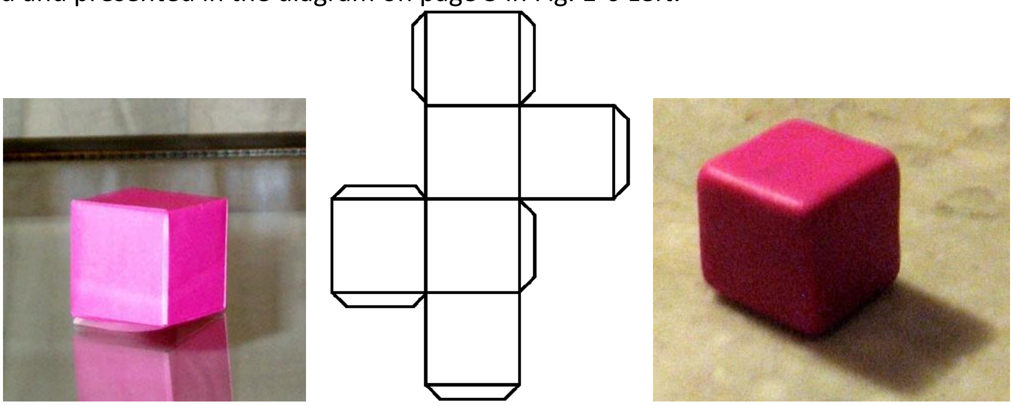


**Fig. 1-4** Tangible Cube Representations

In representing and/or shaping a similar cube in a material or three-dimensional structure (Fig. 1-4), the designer has to think of many more aspects of the cube than in the case of sketching solely on paper. While trying to shape and form the cube, one has to make decisions on the fly about size, ratio and proportion, whilst producing and constructing a geometric object. By making use of tools, like for example; scissors, knife, ruler, glue, pliers, spatulas, etc. and a particular material (i.e. paper, cardboard, clay, sheet metal etc.), the designer supports the ideation process and the representational quality of the cube progressions in three-dimensions.

After tinkering and experimenting with several possible outcomes (iterative instances) the designer arrives at having many different cubes. All cubes represent and present manifestations within or outside the limits (set off constraints) of the designer's scope and ideas about the initial task, problem definition, and solution space.

Whilst materialising, constructing and representing the various cubes the designer creates knowledge and understanding of the problem space. At the same time ignites insight and feedback on all the essential elements of size, dimension, space, structure and construction needed to further the design process. Simultaneously the aspects of form, shape, aesthetic value and creative experiment are addressed and hitherto strengthen the problem-solving and design outcome (Fig. 1-6 Right, page 5).

Another beneficial factor in using the material-shaping-process is the allowance of ambiguous, uncertain, or accidental happenings (cookie luck). During tinkering and toying, the designer allows the unknown and unexpected into the process. Events that happen all of a sudden while cutting or shaping, setting off directions that are fully free from thought (intuition) or steered manipulation. In the event that something goes 'wrong' with the cube, the designer will continue to alter and change the shape to his liking without being distracted or misled by any fixed directions or preconceived notions.

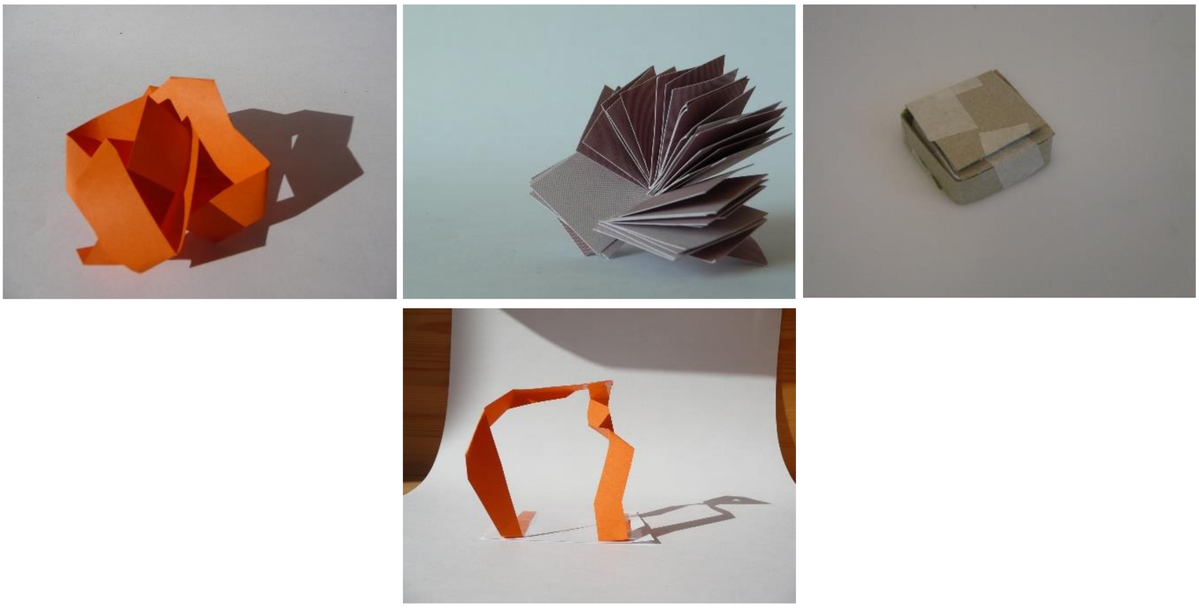


**Fig. 1-5** Tangible Serendipitous Cube Representations

The outcome of the cube-shape might not look completely as envisioned earlier in the process (Fig. 1-5). Because of the ambiguous and self-directing of material flaws or the consequences of tool-actions including the designer's limitations in skills and insight, one might accidentally stumble onto something completely 'new' and inspiring in form and shape.

## 1.2 On Intuition and Cognition in Support of Mnemonic Networks in PCP and/or PEP

Much research is dedicated to understand and come to terms with the intuitive qualities and traits of humans and the role it plays in for example memory and experience in judgment and problem solving (Dreyfus & Dreyfus, 1986; Meehl, 1957; Miller & Ireland, 2005; Lehrer, 2009;). Intuition in the context of discovery evolved out of the philosophical tradition that clearly implied intuition as a means of discovering basic truths unconsciously. Kahneman et al. (1974) challenged this concept stating that intuitive judgements are often misguided since they are overdetermined by a variety in cognitive heuristics. However, in some cases cognitive heuristics can be helpful if appropriately invoked (Nisbett et al., 1983). Determined cognitive heuristics such as representativeness and availability, and underdetermined normative considerations such as sample size, base rate, and regression effects implied this reasoning. While acknowledging that cognitive heuristics can sometimes be helpfully and appropriately invoked (Nisbett, Krantz, Jepson, & Kunda, 1983), the critical consensus clearly implies that intuition is frequently if not typically a systematic source of error in human judgment (Ross, 1977). We doubt this consensual reasoning very much, since it lacks in our opinion very much to take into account the advantages that individual knowledge and experience entails invoked through intuition (Bowers et al., 1988; Wendrich, 2009). Uncertainty and unexpected insights, decisions and choices (intuited) are particularly of interest and highly relevant to creativity and design ideation especially in the context of discovery (Reichenbach, 1938; Polanyi, 1966; Gigerenzer, 2007; Wendrich, 2009). Thus, human cognition is by its very nature intuitive, it inevitably involves the activation of internal and external mnemonic networks by relevant information (Anderson, 1983; Worthen & Hunt, 2011). What differs from one person to another is the nature and amount of information that has already been mnemonically encoded, as well as the complexity, gradient, and speed of the inter-associative connections (Andersen, 1983; Mednick, 1962; Simonton, 1988; Mlodinow, 2009). When a productive hunch or insight goes considerably beyond the information given (Bruner, 1961-1965; Westcott, 1968; Thaler & Sunstein, 2008; Lehrer, 2009; Wendrich, 2009), it is often described respectfully as intuitive, and people who are especially adept at generating productive hunches are often deemed intuitive in this qualitative sense. In essence we could say that everyone is considered intuitive, so far as clues to coherence activate relevant mnemonic networks. According to Worthen et al. (2011), mnemonics are useful in almost any situation in which learning and memory are the goals, but one size does not fit all. The effectiveness of a mnemonic requires that the technique matched to the particular circumstances of application (Worthen & Hunt, 2011).

## 1.3 The Rawshaping Formfinding Paradigm (RSFF) and Frame of Mind – Early Phase Research

In the light of the aforesaid, RSFF emphasis on 3-D intuitive interaction design (IxD) where the designer is affected, engaged, and immersed in conjunction with hybrid design tools (HDT) (e.g. virtual formgiving) to develop ideas and/or innovative concepts during the product creation process (PCP) and/or product engineering process (PEP). The mix of real- and virtual worlds (hybrids), enable the designer to freely transform, translate, and manipulate two- and/or three-dimensional objects that become manifested in both the real and the virtual realms. In terms of timing, speed ratio, and clock frequency of the sequential process steps, this blending could be executed either in real-time, near real-time, on demand, or based on choice-architecture. Based on early stage research and investigation (Wendrich & Tideman, 2004) some preliminary aspects and points of interest in mixed reality (MR), in terms of advantageous and disadvantageous issues and topics were synthesized. The following points are construed to mark and envision the RSFF paradigm (See also Chapter 1.5.1):
Apparent advantages of RSFF:

- Bringing out the tacit and tangible knowledge during design processing
- Intuitive meta-cognitive triggering and interaction during design processing
- Computational design as a virtual assistant in design processing

- Allowing and bringing out the idiosyncrasy of the designer
- Decrease in software program-direction steering
- More user control during ideation and conceptualization
- Untethered two-handed interaction with tangible materials

Relevant disadvantages and constraints of current digital design tools and methods:

- Intimate knowledge required of 3-D systems
- High or steep learning curve (threshold)
- Interaction constraints due to program-direction
- Workflow interruptions due to latency and program-direction
- Increase in process execution time in relation to level of expertise
- No intuitive and/or tacit (implicit) input possible

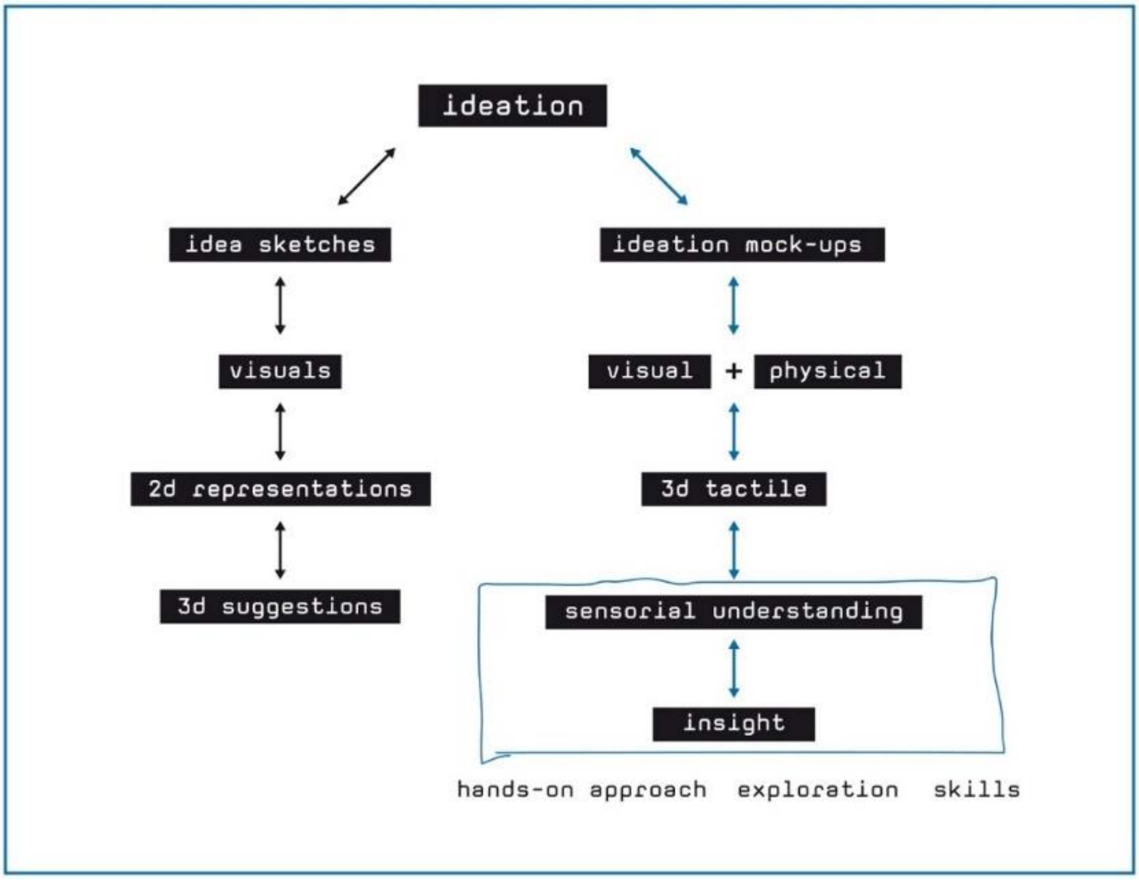



**Fig. 1-6** The early-stage RSFF Frame of Mind ideation process (Wendrich, 2010)

## 1.4 Heuristics in Design Processing

Cognitive research shows that experts can utilize heuristics effectively, and suggests their use of heuristics is a feature that distinguishes them from novices (Klein, 1998). Expert designers may employ cognitive heuristics in order to enhance the variety, quality, and creativity of potential designs they generate during the ideation stage. However, heuristics are not, by definition guaranteed to produce a better design, nor do they systematically take the designer through all possible designs. Instead, heuristics serve as a way to 'jump in' to a new subspace of possible solutions. According to Truex et al. (1999), ill-structured systems need to be developed using a totally different set of goals that would support emergence, growth, and change. Alexander (1964) stated, that the main problem often lies in separating activities surrounding analysis and synthesis, rather than recognizing their duality. With the application of a heuristic, one is not merely recollecting previous solutions in order to apply them to similar problems, but instead, actively and dynamically constructing new solutions. Design heuristics may serve as a starting point for transforming an existing concept, altering it to introduce variation, or define variations among individual design elements. They may be most useful in preventing fixation or lingering on already-considered elements. Our hybrid approach constitutes on the exploration and experimental tradition, where we rely on an assortment of heuristics and operate mostly in a highly unpredictable, stochastic, and/or probabilistic manner across boundaries and often un-structured approaches. The oscillation between real and virtual realities merges the autonomy of user and machine (HMI) this will progressively enrich the intuitive user experience, increase knowledge acquisition, and advance insight in understanding (Csikszentmihalyi, 1990; Wendrich et al., 2009).

## 1.5 Technology Scan on the Potential of Virtual Formgiving in Design Education (2004)

After a thorough technology (Wendrich et al., 2010) scan, the conclusion was that the creation and development of a hybrid design tool (HDT) would benefit the design and design engineering industry. The tool could be an excellent addition to the existing and emerging tools and methods by assisting designers in their physical and virtual design process. The creation of a preliminary RST-framework (Fig. 1-7 and Fig. 1-8) is based on the combination of (a) a thorough technology scan (Fig. 1-9), (b) findings and results from questionnaires, devised for the purposes of a multi-disciplinary survey on the potential of Virtual Formgiving (VFG) in Design Education (Wendrich & Tideman, 2004), and (c) educational embedding of design tasks, processes and experimentation (see Chapter 2). This preliminary RST-framework for the analysis and evaluation of tangible-tactile interactions along a set of parameters and dimensions was devised to come to understand and create insight in the different levels of abstractions and similarities between the physical and digital representation activities. The framework allows us to explore novel devices in the design space, user's intuition, device and tool capabilities, and underlying functionalities/semantics of CAD systems.

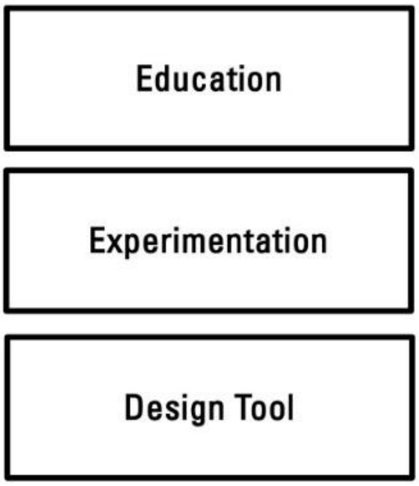



**Fig. 1-7** The Education-Experimentation-Design Tool Research Framework (Wendrich, 2009)

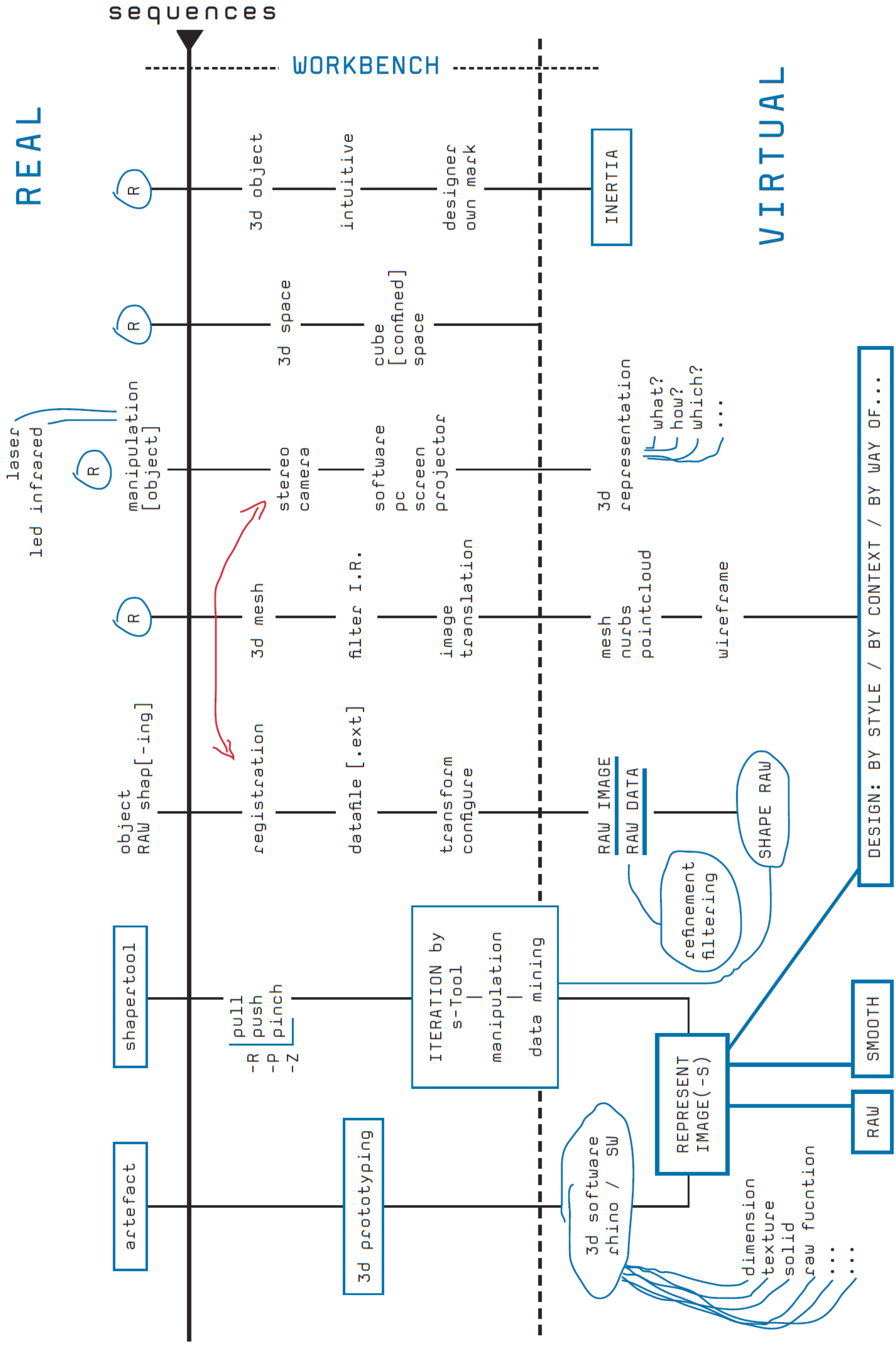



**Fig. 1-8** Physical and Digital Representation (Wendrich, 2008)

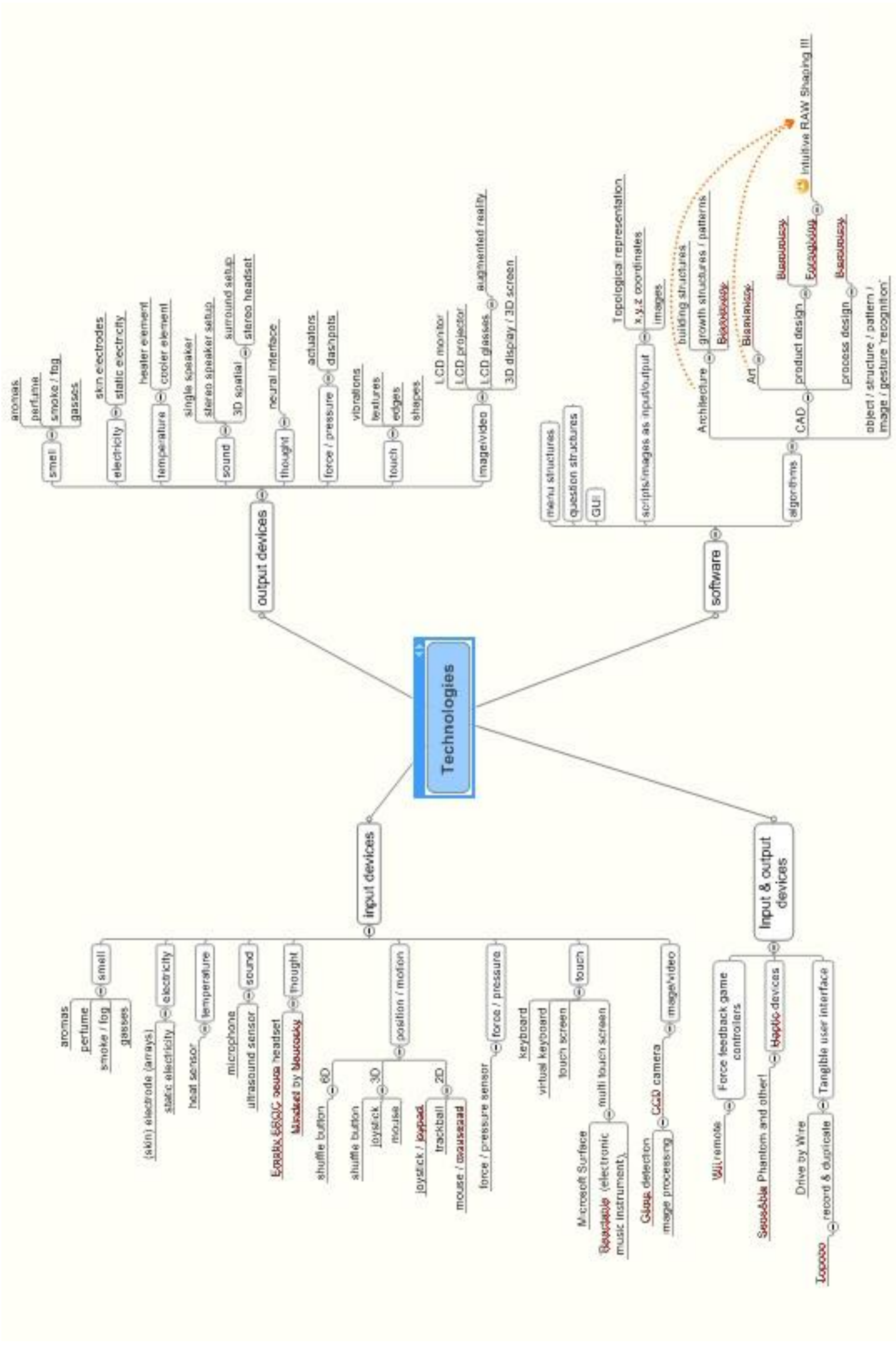



**Fig. 1**-**9** Technology Scan (2010) (Wendrich, 2010)

## 1.5.1 VFG a multi-disciplinary survey on design interaction and representation

In 2004 Wendrich and Tideman conducted a study on engineering technology and industrial design engineering students to investigate the future of VFG in design praxis. These findings and results nudged towards more research and experimentation in the domain of Virtual Reality and Design Tools. Main issue was the implementation of design materialisation and representation assignments in the design engineering program over the last five years. There seems to be a predominance in abstract representation (visual) over material representation (reflective material representation) in most design educational programs (Woolley, 2004). More emphasis was laid on the use of both sensory perception, tactility and sensory feeling (Gilles, 1991; Hartson, 2003) within design assignments, hence the apparent dramatic increase in material representation in conjunction with the abstract representation. Learning in design is enabled through continually challenging abstract representations against material (reflective) representations (Schön, 1983 - 1992; Goldschmidt & Porter, 2004). This comparison between representations reveals gaps that inspire further design activity, experimentation and research.

Combined findings and results lead to possible requirements for further development of RST-HDT's:

- Tool creates more insight and understanding
- Tool has low threshold in learning curve
- Tool increases processing speed in solution space
- Tool implies visual and tangible representation
- Tool triggers easy ideation and conceptualizing
- Tool generates and allows simulation
- Tool allows intuitive un-tethered interaction

## 1.6 On CAD - A Generic View on Computer-Aided Design and PEP/PCP

McCullough (1996) stated: 'We must look very closely at craft. As a part of developing more engaging technology, as well as developing a more receptive attitude toward opportunities raised by technology, we must understand what matters in traditional notions of practical, 'form-giving' work.' This will require the study of tools, human-computer interaction and practice of the digital medium.'

Computers are not programmed to sense and cognitively understand the designer's ideas and fuzzy thoughts that are externalized and transformed during the early-phases of a design process. As stated by Simon (1983); "The computer was made in the image of the human." Furthermore, current computer aided design (CAD) tools have limited capabilities when it comes to translating tangible materials and models into digital/virtual representations. CAD programs use basic geometric mathematical elements and splines curves for shape and form representation (i.e. 2-D lines, arcs, B-Splines, 3-D lines, NURBS).

Key aspects of the design and engineering process, e.g. analogue ideation, intuition, manual skills (i.e. paper modelling, low-resolution modelling), tacit knowledge, and creativity became somewhat trapped and challenged with CAD. Current CAD developments make slow progress towards enactive modes of operation, but still far off from what humans can accomplish in terms of cognitive transformations, sensorimotor representations, through visual manipulations to fully matured formal operations (Sener et al., 2007-2008). The notion of creating playful CAD environments as a transformation technology to address current drawbacks such as complex menus, limited interactive assistance during the design task, formal conceptual design tool and fixation on design routines that stifle users' creativity, ideation and intuitive process are therefore highly important (Wendrich, 2009). These digital approximations ask for a fairly high level of understanding the new shape and new form. Textures and other material properties are lost easily and difficult to add to the digital representation via general standard CAD programs. A different approach could be to let the digital computer handle the process of capturing shape/colour/texture and free the designer from these tedious tasks that disturbs their creative idea stage during the 'iterative' design process.

A powerful concept of RSFF is the combination of iteration speed, fast externalization, reduced level of detail (LOD), thinking-on-your-feet, learning-by-doing, reflection-in-action, reflection-on-action and application of loosely-fitted structures in 2-D and 3-D modelling (Schön, 1983).

## 1.7 The Next Step in CAD & Tools (Bridging the Design Gap)

With the RST-methodology the design and creation of 'low-resolution' models or modelling processes, in conjunction with computational assistance could possibly significantly reduce the computation load, increase performance, enhance interaction and lead to 'fast' tool (interface) response times. This is both true for analogue tools as well as digital design tools.

In comparison, complex digital CAD systems, with plenty of menu/dialog driven computational functions, are expected to create 'steep' learning curves and will have a disruptive effect on transferring the creative flow of ideas into digital/virtual representations (Csikszentmihalyi, 1990; Wendrich et al., 2009).
Therefore, the following hypotheses are framed and based on the assumptions that:

- Fast and responsive design tools with analogue tangible feedback is what designers prefer as a tool of choice.
- Simple tools in combination with low 'creative' constraints should lower the learning curve for the tool. That is what is expected from the analogue representation tests.

# CHAPTER 2- EDUCATION

## 2.1 Educational Testing and Assessment of the RSFF Methodology

Several methods and strategies were devised and used as experiments within teaching and learning contexts, ranging from very abstract-physical assignments to 5-phase design methods (i.e. *idea phase-concept phase-final concept phase-execution phase-presentation phase*). During this educational approach, a seemingly more structured method is assigned to design an artefact. In such we hand students an orthogonal projection (Fig. 2-1) of an automotive design icon (Citroën DS) on A4 paper-format. The elevations are in proportion, but not to a specific scale! The first task is to size-change (scaling) the elevation drawings to an exact dimension: 488 x 180 x 147 mm (Fig. 2-2, top left and top middle). Many students seem to find this a difficult task and noticeably many variations in size-change become apparent. Some students will take no direct action, contemplating, deliberating and thinking about their approach and following step. The assignment was to fabricate, form and shape, in conjunction with a 2-D orthogonal drawing of an automotive design icon, a three-dimensional wire-frame model of this artefact. The material used in most cases is aluminium wire and tape. The study and translation is based on and devised as a representational form study, finding and discovering aesthetic criteria, triggering aspects of form-giving and expanding the geometric vocabulary of novice designers (Fig. 2-2).

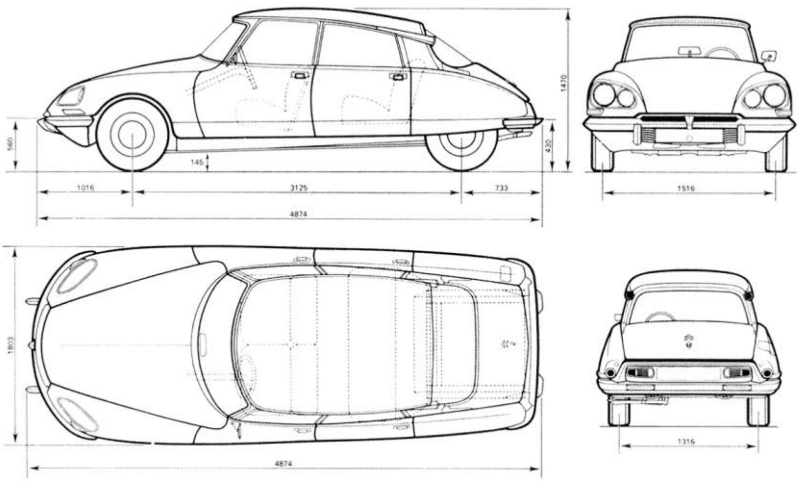



**Fig. 2-1** 2-D orthogonal drawing of design icon

**Educational design task aims:**

1. Translating 2-D orthogonal projection in 3-D tangible form and shape.
2. To discover different design approaches and form giving methods in 2-D to 3-D representation.
3. Finding form and aesthetic criteria in tangible objects
4. Exploring form structure that results from form organization
5. Enhancing tacit knowledge, understanding and imagination

A wide variety and diversity in model representation and/or solutions due to difference in shape and proportions, as well as in form and textures were observed and notable. Learning-by-doing, thinking-on-your-feet, and knowing-in-action are hard to “measure” and at the same time promising concepts for enriching existing design methodologies. After analysis and evaluation of the video data (Jordan & Henderson, 1995) from student sessions, the preliminary results showed that students become less limited in their design process if they use more creative tinkering, randomness and ambiguity. Tacit knowing and tangible modelling complement each other in a way it enhances results while allowing better understanding and more insight. Other advantages are an increase in self-esteem, confidence, value, awareness, passion and sense-of-ownership.

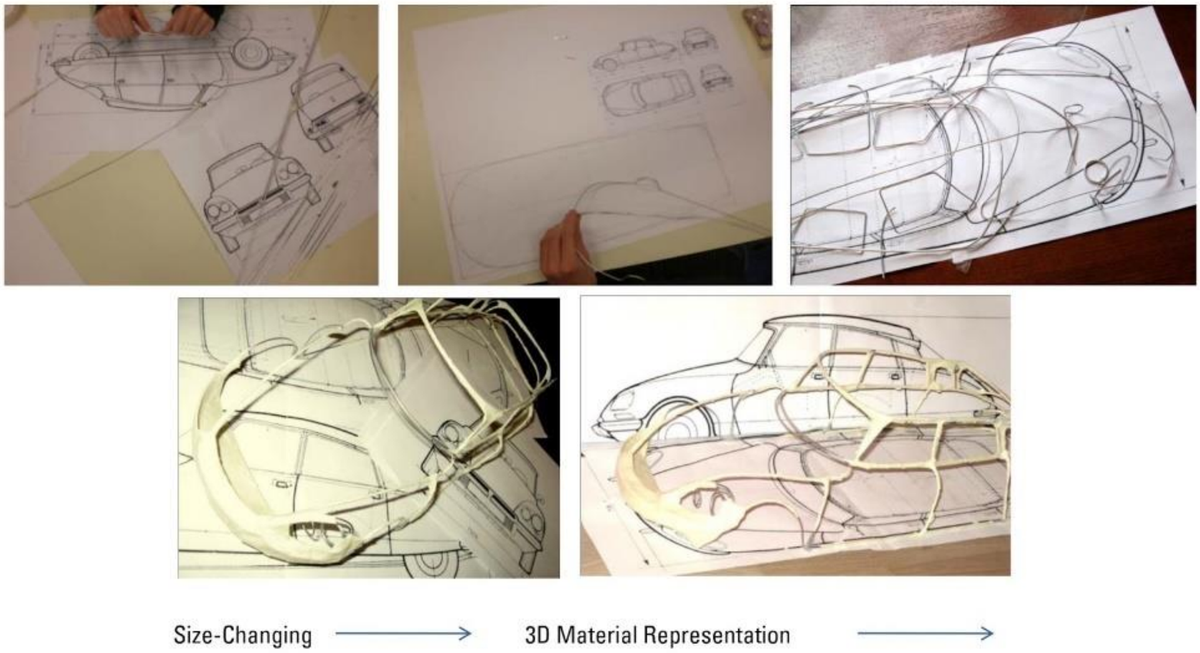



**Fig. 2-2** Educational design experiment on 2-D to 3-D representation (From left to right, top to bottom: size-changing, tangible-tacit manipulation with reflective material, 3-D wire-frame construction, final 3-D representation)

**RSFF Design Task procedure and process for testing the students:**

1. Getting to know and understanding RSFF
2. Setting up of new experiments
3. Enrolling participants in new experiments
4. Capturing and observing RSFF design processing
5. Administrating results of experiments
6. Analysing, evaluating and reporting the captured data
7. Presentation

To obtain knowledge about the effectiveness and emergent methodology of RSFF, the results should provide data, insight and understanding in correlation with the hypotheses postulated in paragraph 1.7.

**RSFF Design Task effectiveness and representation performance in education:**

- Understanding of tacit and tangible knowing
- Knowledge acquisition of 3-D tangible interaction
- Knowledge acquisition of RSFF design processing
- Acquiring insight in 3-D manipulation and representation
- Implementation of the RSFF intuitive 3-D design process

## 2.2 Analysis and evaluation results of educational design task

Two significant modelling methods emerged based on the analysis and evaluation results of this experimentation. Representation was either done by 3-D curves or by slicing. The findings on 36 selected models out of 150 individual iterations made by Bachelor students Industrial Design (Wendrich, 2009 - 2010). The translation and transformation task is devised as a representational form study, finding and discovering aesthetic criteria, triggering aspects of form-giving and expanding the geometric vocabulary of novice designers. All 36 models are placed in a ranking order the best result to the worst result (Fig. 2-3 and Fig. 2-4). The best model has been given number 01 and the worst model is number 36. In Figure 2-5 we show the multi-variables in solutions and representations that stem from the same design task, constraints and requirements. The diversity and variety in solutions and multiplicity in representative quality and interpretation is highly noteworthy and extremely thought-provoking (Wendrich, 2010).


**Fig. 2-3** Selection of 36 models and ranked in order of quality only (from left to right / top to bottom 01-36, whereby 01 is the best executed model representation)

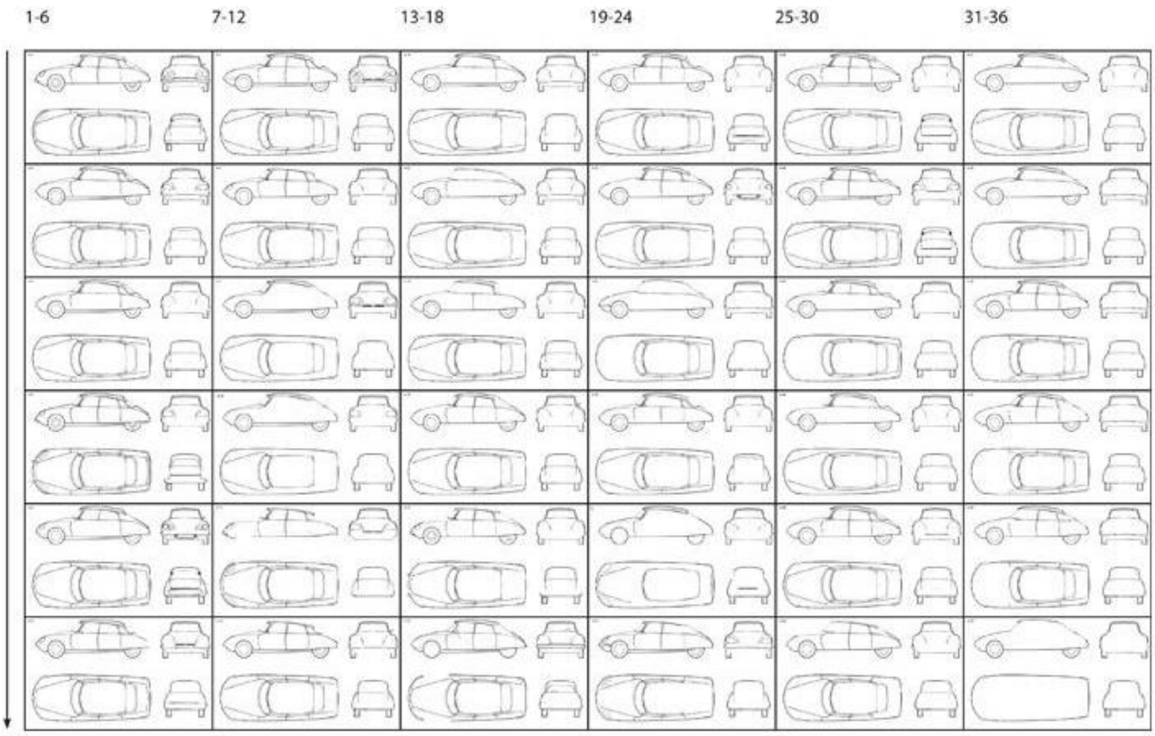



**Fig. 2-4** Ranking of 36 models in order of quality, shape representation and applied slicing-method

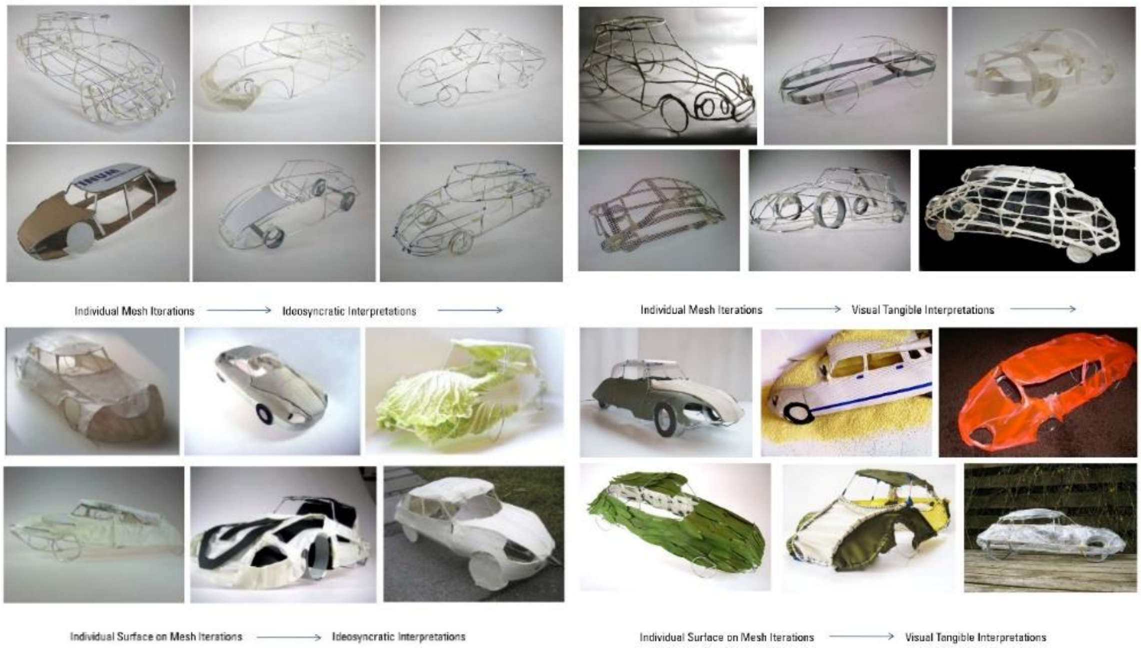



**Fig. 2-5** Wire frame DS and surface texture examples on DS wireframes (showing variety in shape and form, diversity in solutions and representations and a plethora in interpretations)

## 2.3 Interpretation of Form Organization

The interpretation and type of chosen slicing method based on the 2-D drawing determine the outcome. Mistakes and personal perspective in this stage have a direct effect on the model right from the start and will clearly show in the end result. Incorrect interpretations are frequently made. For example: the assumption that front hood midline is the headlight line. This is clearly not the case as shown in Figure 2-6.

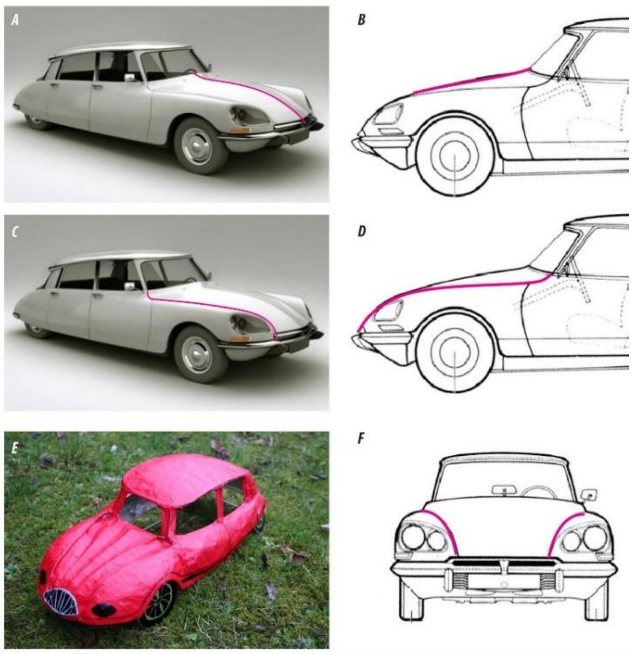



**Fig. 2-6** Interpretation modelling icon artefact

The front hood is a difficult part in the shape of the Citroen DS. Figures 2-6 A, B, C, and D show the correct corresponding lines in a 3-D model of the Citroen and the drawing. Figure 2-6 F shows that also a front view doesn't really clarify the situation. In this case actually only a 3-D model shows correctly how the model should be build. Another possibility is a 'see through' line of the front hood in the side-view of the drawing. Besides the fact that the drawing is hard to interpret, there is one incorrect interpretation that happens frequently which becomes clear from carefully inspecting the drawing. The pink line in Figure 2-6 D is frequently mixed up with line B. The result is that the front-hood is one piece in the model, without the characteristic separation of headlights and front-hood as Figure 2-6 E illustrates (Fig. 2-4 - DS17). With this the aesthetic and functional appeal of the model becomes significantly blurred and whimsical in representation.

## 2.4 Defining Mean Quality (MQ) for a Simple Effective Representation of an Automotive Design Icon

Modelling and interpretation of a 3-D model/wireframe is all about relations and distances between wires, views, surfaces etc. Correct distances between the wires give the model the right proportions and aesthetic quality. Contour lines of 3-D shapes are sometimes only visible from one specific 3-D view angle with a very narrow deviation from this angle before the next contour line appears for the same 3-D shape. These curved lines can be used as a starting point for constructing curved contour lines or sectional slice lines. Some of the curved lines can represent a hard separation edge between two or more surfaces. These line elements are still viewable from a much larger angle and signify a real distinctive 3-D trackable part on the surface of the 3-D shape.

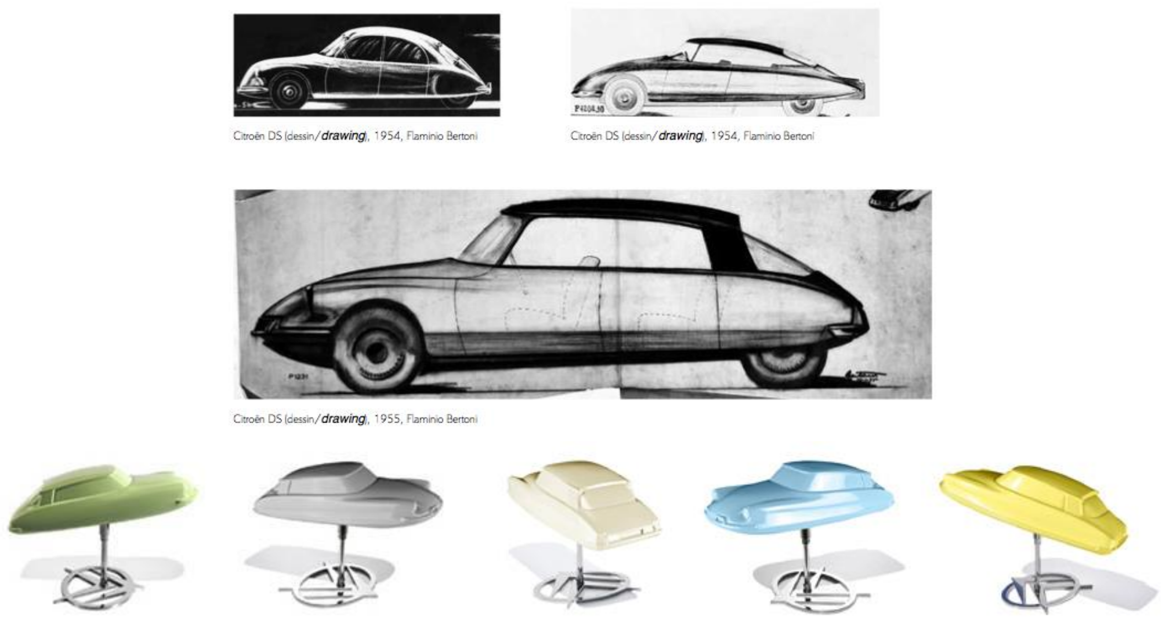



**Fig. 2-7** Citroen DS (2-D drawing and 3-D sculpting), design Flaminio Bertoni (1955)

In applying this knowledge about curved lines for example to an automotive design icon like the Citroen DS model from around 1955 (see Fig. 2-7) one can distinct some specific lines and curves that represent this automotive model in a simple yet effective manner.

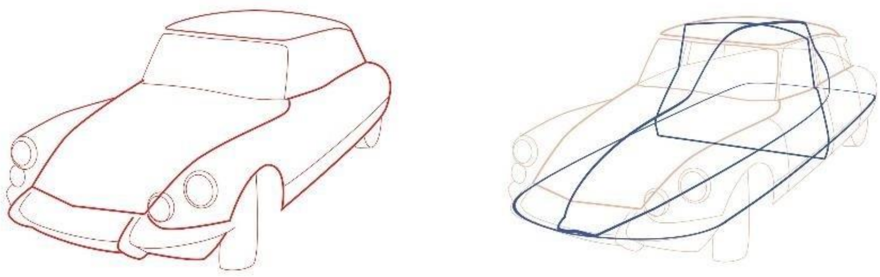


**Fig. 2-8** Two Citroen DS modelling approaches: curve contour lines (i.e. multiple flow lines) & sectional slice lines (i.e. 3 dominant slice lines)

## 2.5 Modelling in Slices vs Modelling in Curves

From the earlier educational tactile studies between 2004 and 2009, two significant modelling methods emerged (Fig. 2-8) after evaluating and analysing the tangible-tactile results of 150 individual iterations concluding this experimentation. Representation was either done by 3-D curves or by way of slicing (i.e. merging of elevation views).

### 2.5.1 Modelling in slices without total overview

In the case a designer builds the model from slices derived from the orthogonal drawing (Fig. 2-1) there is no need to have a total overview of the shape and form in advance. If the designer works precisely and uses the side- and top-views there is no chance of going wrong if the side- and top-views are correct and clear. However, types of problems that are found in this type of modelling are (Fig 2-9):

- Double use of side-views / elevations
- Location and placement of slice (-s)
- Missing or omitting a view(-s)

**Fig. 2-9** Examples of slicing and significant modelling problems

a) Double use of side-views / elevations: To make a 3-D model an inviting option is to double the side-view and then connect the two parts (i.e. similar to extrude in CAD). This is an easy way to get a 3-D model, but this model will never get the right shape and form. In the line-up of the models (Fig. 2-3) the “artefact cars” with a double us of the side-view all end up at the end of the row. All models with the use of a double side-view totally miss the translation and articulation of the front- and back view.
*Observation: One side-view should be used in the middle of the model to get a good result.*

b) Location/placement of slice (-s): The location of the slices can cause problems. In a front or back view it is not clear where precisely the slice should be placed. It can be located directly

at the front or more in the middle. Also for the top-view it should be clear at which level this top-view is visible. In the models the top-view is mainly used as the lowest slice, but in fact the DS narrows down at the bottom. This means the top-view should be placed higher than the bottom.
*Observation: To get a good result it should be clear where a specific view or section is located.*

c) Missing or omitting a view (-s): The best result will be gained when every view is translated in the model. The absence of front and side-views leads to inferior models.
*Observation: To get the best result every view should be translated in the model.*

### 2.5.2 Modelling in 3-D curved lines

Curved lines from the 2-D drawing have been used to create a 3-D model. The lines that are picked for the modelling are not exact outlines or sections but fluent lines that cover more than one view (Fig. 2-10 and Fig. 2-11). When modelling in 3-D curved lines the scaled 2-D drawings (view and elevations) are being used to create 3-D models. The chosen lines for executing the curved line model are not exact outlines or translated sectional views but flowing and fluent lines in 3-D space that cover more than one view or section and are combined / blended in the interpretative model/wireframe.

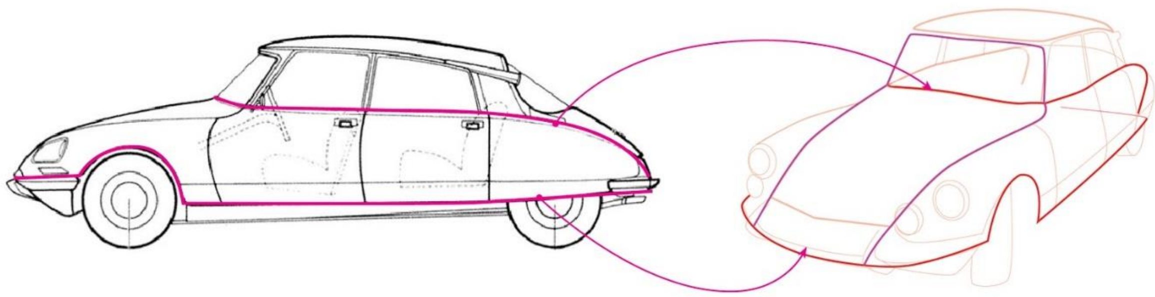


**Fig. 2-10** Various fluid curves are used for 3-D model interpretation and representation

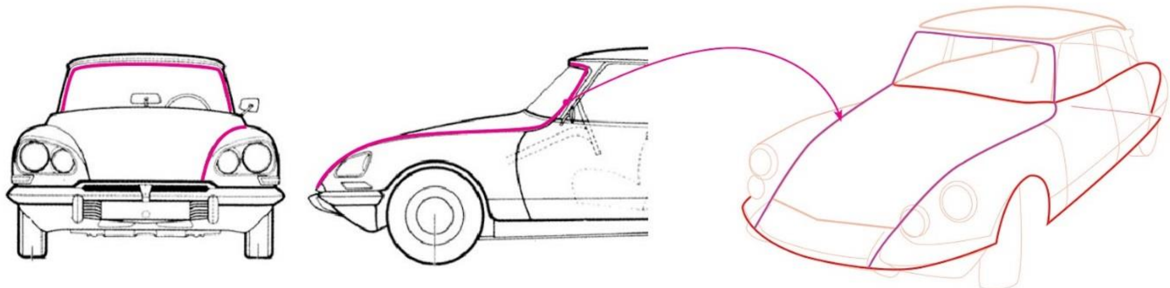


**Fig. 2-11** Various fluid curves are used for 3-D model interpretation and representation

The designer has to have a good mental image, detailed insight, precision intent, and understanding of the total shape before commencing the modelling (Fig. 2-10). Since all the views and elevations merge into one or several fluent and curving lines the shape and form should be clear in advance (mental image and spatial insight). However, 'Distortions in the visual perception of three-dimensional form can be corrected by tactile observations' (ibid. W. Gilles, 1991). This human reflective quality pertains to the ability to sense (i.e. feel, touch) and interpret through haptic perception of objects / artefacts. In effect the correction and adjustment of the shape and form by means of direct tactile-tangible feedback from touch and feel of the wire-frames, surfaces and textures (Schön, 1983; Gilles, 1991; Brereton, 2004; Grunwald, 2008; Wendrich, 2009).

**Fig. 2-12** Modelling in 3-D curved lines, shown is top-ranking model (see also Fig. 2-4 - DS1)

Modelling and interpretation of shape and form in 3-D curves generates the best representation and generates superior models if set-off against the slicing methods. Based on the aforesaid, we conclude that to establish a MQ, 3-D curved lines models are *virtually closest to the real* model of the Citroen DS car (Fig. 2-7). The actual Citroen DS was designed by a blended method of representational design methods, 2-D and 3-D sketching and drawings in conjunction with 3-D sculpting and prototyping (Fig. 2-7).

## 2.6 Research Question

The preliminary results and outcomes from the early-phase educational design tasks, showed promising outcomes and progressions.
In correlation with and aligned to these early-phase experimentations, seven design process test-benches were devised and developed to study and investigate various interaction modalities in congruence with execution time during an iterative design task process. The expected data coming from these seven tests are generated to gain more understanding, knowledge and apprehension in the relation between interaction modality, tool use, affordances, speed of interaction, iteration performance, and representation quality. The end-result of a design process or design task is not the only factor determining the final ranking. The iterative process (i.e. speed, duration, affordance) in itself is equally of importance and weigh on establishing the final ranking. Chapter 3 explains the process more in detail.

**Research Question:**

*How fast (i.e. interaction-iteration speed) can one make a qualitative representation based on implicit (tacit) knowledge and skills, explicit tools, constraint-based execution, predefined time-set and reflective material?*

## 2.7 MQ Established for Seven Representational Tests

In Chapter 3 the MQ for the seven representational tests and experimentations will be based on the MQ definitions as described and established in Section 2.5. We defined a weighted ranking that signify the relation between quality descriptors, tool interaction and iteration speed. The following formula will establish and generate the mean and will result in a weighted rank:

$$(T + Q) / 2 = R \qquad \text{[Eq. 2-1]}$$

Key to symbols: Q = Design Ranking
T = Ranking Average Iteration Time
R = Overall Test Ranking

The average is easy to calculate from two values and ranking on the list, except when a tie occurs this will generate a problem. For solving the tie as best as possible, a new tie break column (TBC) is needed. In effect, the weighted ranking with the tie break in the new column is calculated using the following formula:

((R * max_data_rows + T) * max_data_rows) + Q = TBC [Eq. 2-2]

The symbol "max_data_rows" equals the value that represents the length of the list per experiment. This number is not a fixed rule for the "tie-break calculation" (TBC) strategy, it helps to get rid of some unwanted floating-point number calculations. This way integer numbers are used for calculation, even if this means the numbers can get quite large very fast.

Formula Eq. 2-2 in algebraic notation:

$$a \cdot x^2 + b \cdot x + c = d \quad \text{[Eq. 2-3]}$$

In eq. 2-3 the variables *a* to *c* follow the order of importance for the input data columns. The output variable *d* will result in an unique "tie-break" number. All rows from the spreadsheet should have an unique number to be ranked and sorted. Finally, the data points can be plotted in a XY scatter chart.

The calculation results are sorted in ascending order, as described and shown in the analysis and evaluation diagrams of the seven experiments (see Chapter 3 and Appendix A).

### 2.7.1 Correlation coefficient for the trend lines

To improve the readability and facilitate easy comparison of the various experiment diagrams, we use trend lines (3rd order polynomial) instead of actual real data points. Therefore, the visualization of indicative trend lines are an approximation, showing the correlation coefficient (CC) between the actual number of hits on the weighted data points including data point deviations.

The choice for 3rd order polynomial trend lines was initially based on a graphical approximation of the scattered data points per experiment. A trend line with the availability of two curvatures would fit nicely. When reviewing the CC from the first order (linear), over second order, to the third order polynomial trend line, the optimized curve fitted trend line showed too little increase in approximating the actual data points. Further increase to an even higher order polynomial trend line would not add more precision, only more mathematical and graphical complexity. Main purpose of the trend line is to visually reduce the number of curvatures between the data points and visualizes a possible mathematical trend curve in the scattered data.

A perfect match (100 %) equals a full CC that targets all actual data points, however in all cases this condition will never be fully met. The CC is defined as a numerical value between -1 and 1, where 0 means no correlation at all. The plus indicates an ascending slope, whereas the minus depicts a downward slope. In diagram Fig. X7-13 all seven trend lines are shown and illustrate clearly the variety and diversity of data points over the seven experimental results.

The correlation coefficient (CC) is calculated based on the formula = $\dfrac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2\sum(y-\bar{y})^2}}$ [Eq. 2-3]

## 2.8 Preliminary Conclusions of the Early-Phase Education Test Results

In conclusion the early findings show that early-phase educational experimentations, design method and system could provide a very useful platform or research framework for the development of new and more sophisticated design representation tools. The aim is to fill the voids between the analogue real and the virtual real by making use of tacit-tangible skills and traditional tools. The former in combination with an intuitive augmented workbench and common sense provides a potentially huge array in data and information on design and engineering processes. The findings and results of early-phase fundamental research in the educational field and laboratory tests, show that intuitive physical rawshaping and formfinding (RSFF) are instrumental in the creation of understanding, insight and change while processing in the design context. To be assisted by a virtual computational device (RSFF-HDT) the design process, for example in the ideation phase (i.e. fuzzy front end), will be enhanced, augmented, and improve the representational design process significantly.

# CHAPTER 3- SEVEN REPRESENTATIONAL DESIGN EXPERIMENTS

## 3.1 Introduction to Testing and Experimentation

In this Chapter seven tangible-haptic representational configurations and set-ups are introduced. The seven experiments are specifically designed and build for tacit-tangible experimentations and testing purposes. All seven experiments are tested with a variety of users with various skill- and expertise levels in order to establish a heterogeneous distribution in representation results. The **aim** of the experimentations is to measure, explore, and qualify the effectiveness of untethered and tethered tool use; apparent routines, mediation of restraints, signs of flow and stall, as well as gestural and skill development. Therefore, the assumption is that all seven individual experiments combined, will provide more knowledge, detailed insight and better understanding in intuition, tacit knowing, user-interaction (UIA), tool use, skill application, tactile perception, tangibility, and representation. Furthermore, all seven experiments are also based on the findings and results that stem from educational exercises; particularly the DS-Icon assignment (see Chapter 2). The core driver of each experiment is that each participant has to imagine (i.e. mindset, tacit knowledge) and interpret (i.e. mental image) how to reconstruct an automotive artefact into a 3-D visualization. In effect, to translate, manipulate, and transform a 2-D drawing (orthogonal projection) into a 3-D perspective representation. The externalization of tacit-tangible knowledge about the artefact, to trigger spatial insight, performance speed and enhance cognitive understanding of the artefact is key to the seven experiments. To bring out these factors of knowing is highly probabilistic, ambiguous and idiosyncratic in terms of interpretation and perception. Furthermore, the intuition and experience of the participants are tested with a variety and mixture of representational design tools (i.e. traditional analogue and digital), time- and constraint-based. The tests are performed by bachelor and master students Industrial Design Engineering (IDE) of the University of Twente. Additionally, we include expert designers and staff members of Engineering Technology (ET) in the user-test groups. Every experiment will be performed in a controlled setting in conjunction with a facilitator for guidance and observation. All experimentation and individual testing are videotaped and will be analysed afterwards. Video Interaction Analysis (VIA) (Jordan & Henderson, 1995) is used to analyse and evaluate the outcomes and results.

## 3.2 Experiment 1 - Pencil and Paper Sketching

Experiment 1 (X1) is based on freehand pencil sketching on standard A3 size of paper[1]. A group of 25 individual participants (19 male and 6 female) executed this first test. This X1 group consisted of 60 % BSc. (novice) and 20 % MSc. students (advanced) in the age of 18-26 years. The final 20 % were expert designers (i.e. lecturers IDE) in the age of 25-36 years. A detailed overview of participants is shown in Table X1-1.

**Table X1-1** Overview participants Experiment 1

| | | | | | | |
|---|---|---|---|---|---|---|
| **Participants X1** (Pencil & Paper) | 25 | 19 | 6 | 15 | 5 | 5 |
| | 100 % | 76 % | 24 % | 60 % | 20 % | 20 % |
| | 18-36 years | | | 18-26 years | | 25-36 years |
| | **Total** | **Male** | **Female** | **Novice** | **Advanced** | **Expert** |

[1] https://vimeo.com/10381990

### 3.2.1 Typical setup X1

The X1-setup is kept very simple and effective in lay-out. A chair and a table allow the participant to comfortably sit and work during the test. In X1 traditional design tools are provided, such as pencil, fine-liner, and an eraser. A five-minute time limit is set for this experiment. However, in some cases we allowed additional time (Fig. X1-03).

### 3.2.2 Design representation task description X1

The participant is seated during the duration and execution of the test. The facilitator's role is to instruct, observe, and capture the user-interaction (UIA) on video (Fig. X1-01). The facilitator provides a brief set of instructions and explains the X1 procedure as follows;

- Facilitator shows and hands the A4 to the participant and explains the meaning of the 2-D drawing (Fig. X1-01).
- The design task of X1 is explained to the user.
- The template is placed on the A3 sketch paper and explained to the user.
- The facilitator asks consent of the user to capture UIA on video.
- A time constraint of 5 minutes is instructed.
- Start and execution of design task X1.

**Fig. X1-01** Setup Pencil Sketching bench (X1)

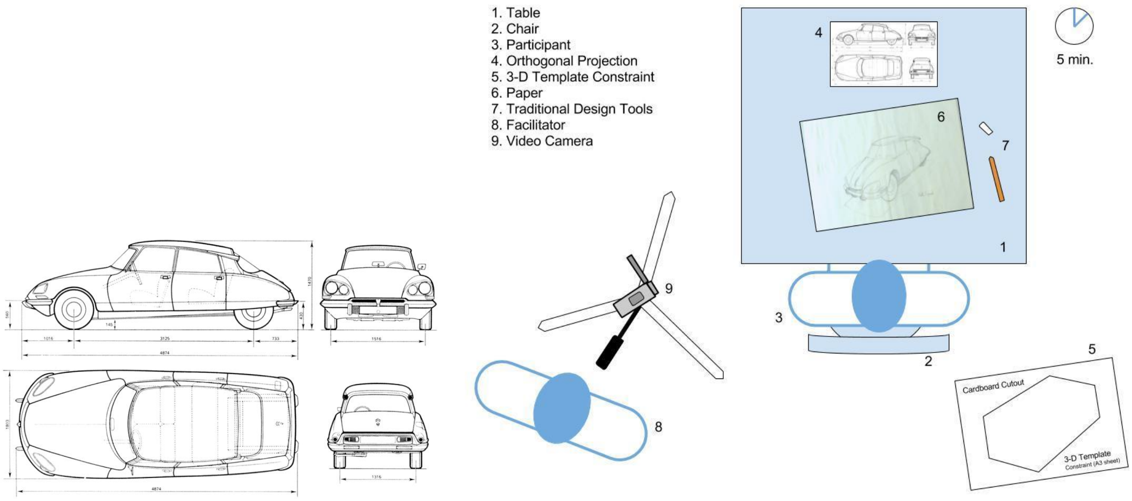



**Fig. X1-02** Orthogonal drawing (4) of a Citroën DS and diagram of setup X1

## 3.2.3 Design representation task X1

Individual participants are asked to interpret and create 3-D sketches based on the orthogonal drawing of the artefact (Fig. X1-02 left). The goal is to 3-D sketch, represent, and interpret as fast as possible the main features and characteristics of the automotive artefact. A perspective template enforcing a size constraint (Fig. X1-02 right and Fig. X1-03) is used to serve as temporary placeholder. The perspective template provides the participant with an initial direction and position on the sketch-plane. This constraint-based procedure is necessary to be able to compare (rank) the individual sketches, effectiveness and quality of the results after the experimentation concluded.

## 3.2.4 User interaction X1

The designer has to have a good mental image, detailed insight and understanding of the total 'volumetric' shape before commencing with the modelling (Fig. X1-03). Since all the views and elevations merge into one or several fluent and curving lines the shape and form should be clear in advance. To test the methodology in this setup, we observe the effectiveness, ideation skills, visualization speed, apparent tacit knowing and the threshold in learning. We measure the interpretation in relation to the artefact representation, qualitative results of the individual process outcome with the sketching tool setup in conjunction with the process speed of interaction. We compare all the results from this sketching process and rank (see Table 1-1) them based on the established MQ (i.e. shape and form vs iteration speed).

**Fig. X1-03** Start of test procedure participant with sketching constraint

### 3.2.5 Tangible test results X1 (selection)

In Figure X1-04 to Figure X1-09 a selection of X1- representation results are shown. The presented selection has no particular order or based on qualitative indicators. The images show the variety and diversity in solutions and representational visualizations.

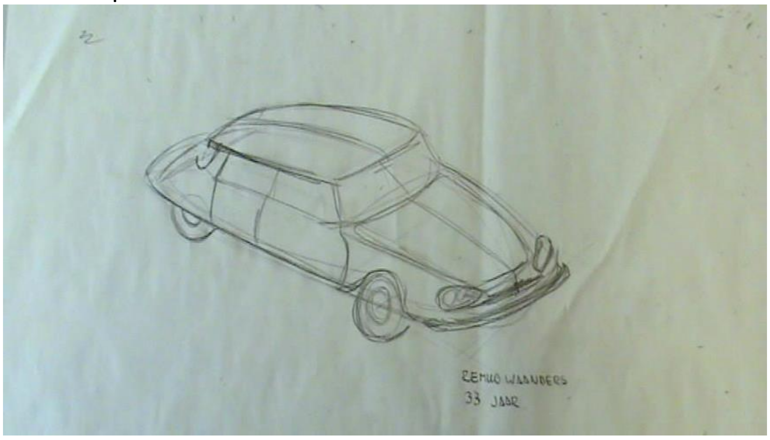



**Fig. X1-04** Sketch participant no. X1-15

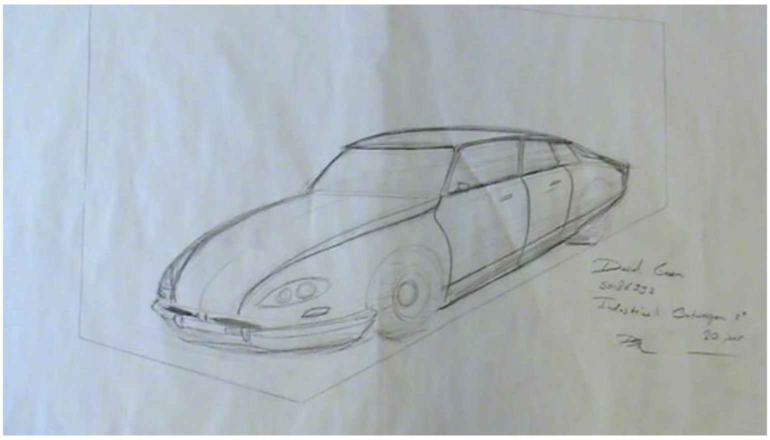


**Fig. X1-05** Sketch participant no. X1-07

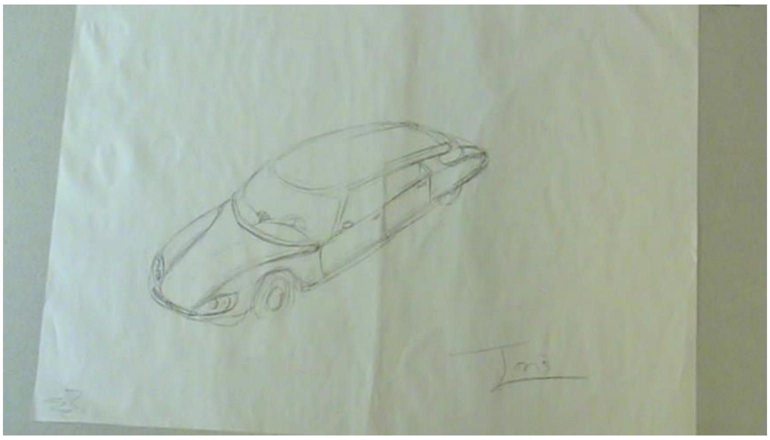


**Fig. X1-06** Sketch participant no. X1-23

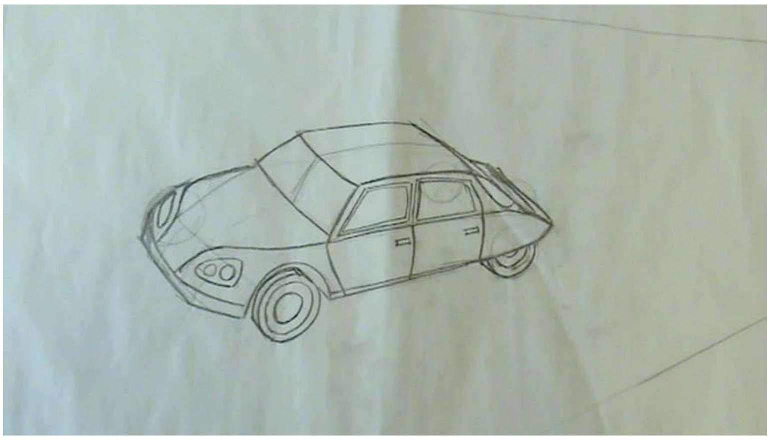


**Fig. X1-07** Sketch participant no. X1-12

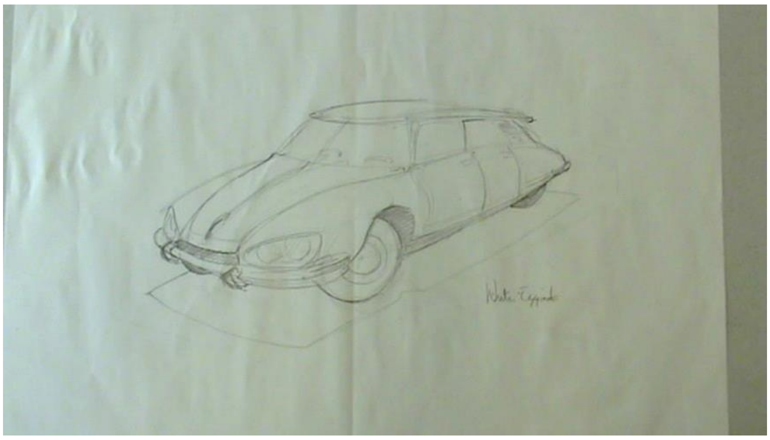


**Fig. X1-08** Sketch participant no. X1-22

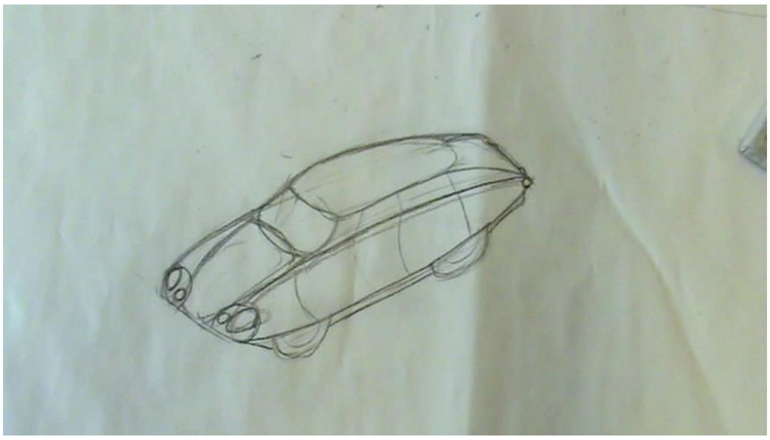


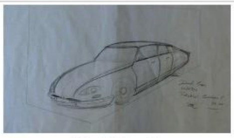
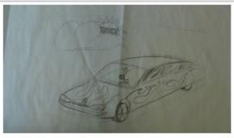
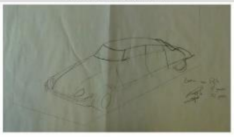
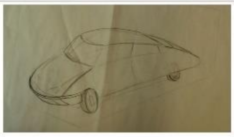
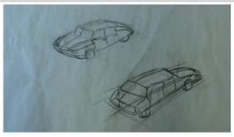
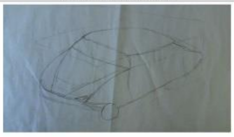
**Fig. X1-09** Sketch participant no. X1-11

For more results of other participants see Table X1-2.

### 3.2.6 Overall ranking results pencil sketching test

**Table X1-2** Time & quality combined (left to right - top to bottom)

Left to Right - Top to Bottom (25 results)

| | | | | |
|---|---|---|---|---|
|  **X1-22** Wouter |  **X1-03** Dennis |  **X1-25** Wilco |  **X1-15** Remco |  **X1-07** David |
|  **X1-10** Derk |  **X1-21** Ruben |  **X1-08** Gerben |  **X1-09** Frank |  **X1-05** Christiaan |
|  **X1-12** Henk |  **X1-06** Sophie |  **X1-13** Leon |  **X1-24** Jose |  **X1-02** Marijn |
|  **X1-17** Evelien |  **X1-14** Tineke |  **X1-01** Tom |  **X1-11** Frederiek |  **X1-18** Paul |
|  **X1-20** Willem |  **X1-04** Jeroen |  **X1-23** Joris |  **X1-16** Els |  **X1-19** Marijn |

In Table X1-2 the final ranked result are shown for experiment X1. The top left result equals position number 1. From left to right the numbering increases until the bottom right. This position equals the last position, based on the combined time and quality qualifiers.
Ranking the results makes it easier to see the gradual differences, from poor results all the way up to the best result. When the quality is weighted by the factor iteration time rank, we can differentiate between fast and slow iterations in relation to similar quality results in shape and form organisation.

While ranking by the iteration time is straight forward, ranking by design quality is quite subjective. The criteria for ranking the shape and form organisation (quality) was mainly based on the MQ as explained in Sections 2.4 through 2.6. Translation from 2-D to 3-D with respect to the original proportions was the next qualifier. And the level of detail (LOD) was another important qualifier. The experiment description did not mention the designer to aim for highly detailed drawings, though the pencil and paper medium allowed for a lot more detail. This detailing pointed the facilitator to interrupt the experiment and terminate or extend (in later experiments) the session.

### 3.2.7 Analysis and evaluation X1

In figure X1-10 individual iteration and processing time of the 25 participants are shown of X1.

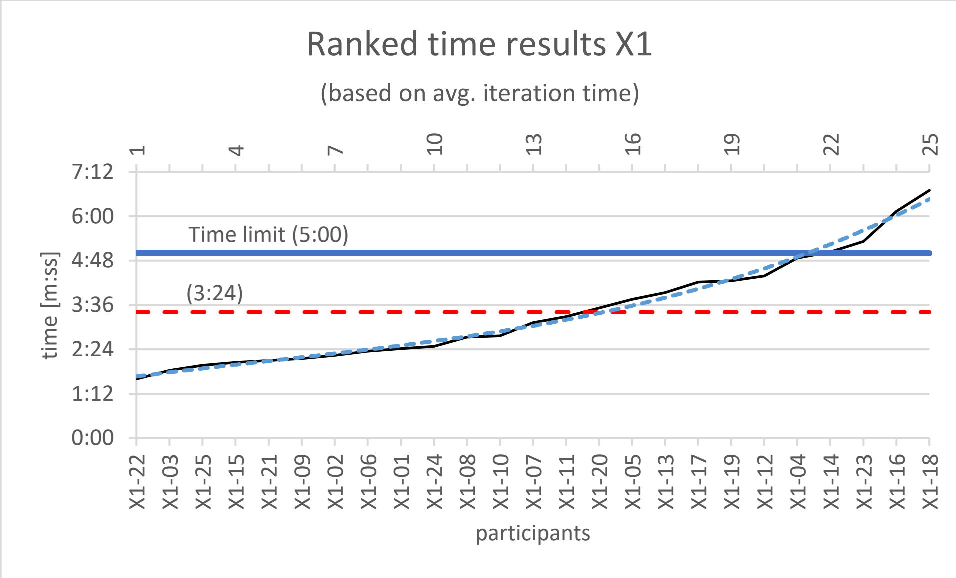



**Fig. X1-10** Ranked by time (left = fast, right = slow)

Presented in Fig. X1-10 are all 25 individual results (black jagged line). A steady curve (3rd order polynomial) trend line (blue dashed curve) results in a CC = 99,6 %. The average iteration time is 3’ 24” (red dash line) which stays well below the 5 minutes time limit.

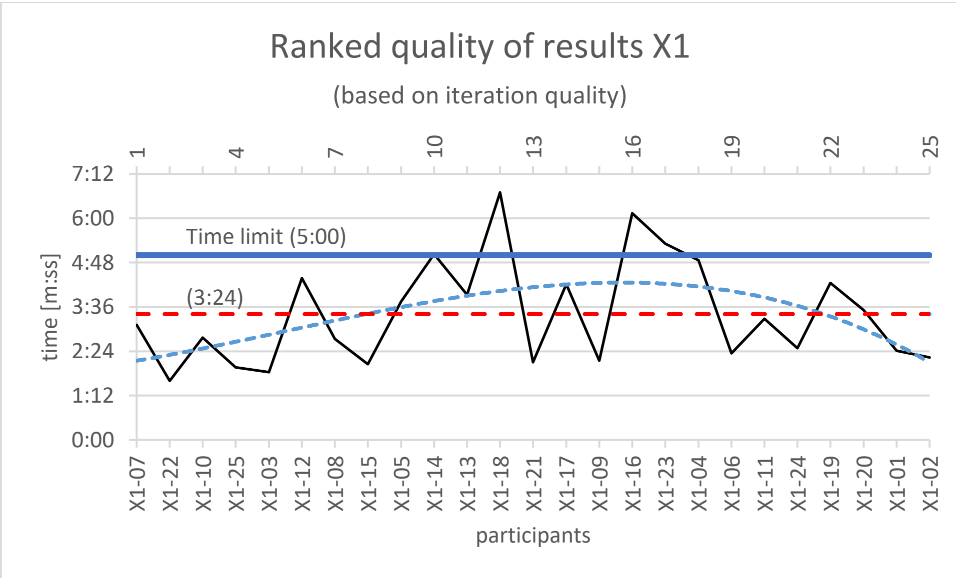



**Fig. X1-11** Ranked by quality (left = good, right = sufficient)

When we display the quality ranked iterations as in Fig. X1-11, the data points get more irregular and jagged (black line). The (3rd order polynomial) trend line (blue dashed line) becomes convex curved with a CC = 51,3 %.

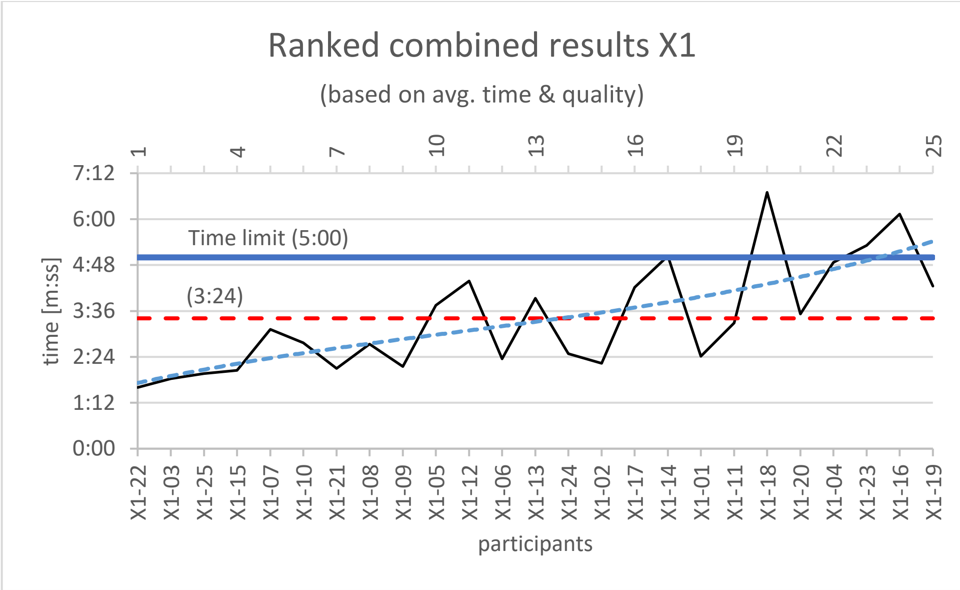
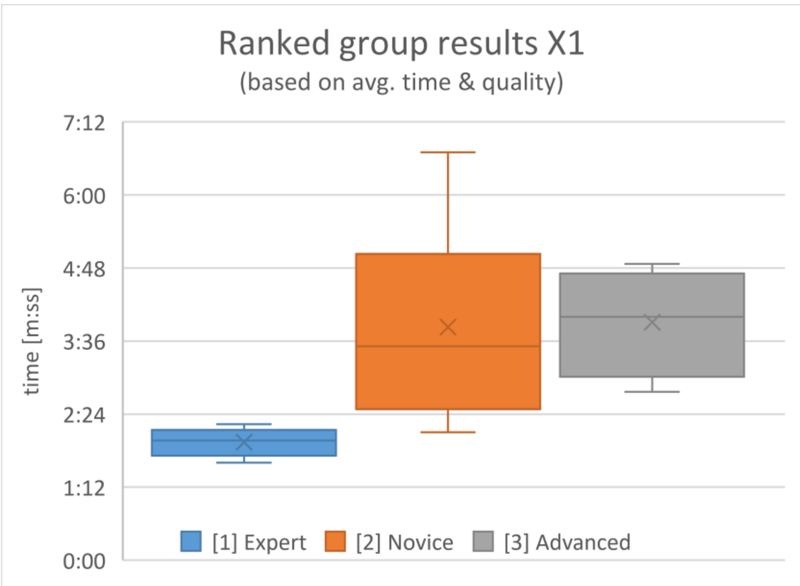



**Fig. X1-12** Ranked by combined results (left = good, right = sufficient)

In Fig. X1-12 we present the individual quality ranked iterations (black jagged line). The data points get more smoothed out and the (3rd order polynomial) trend line X1 (light-blue curved dash line) becomes more straight with a CC = 74,0 %.




From left to right

1st Expert X1 (Pencil & paper)

2nd Novice X1 (Pencil & paper)

3rd Advanced X1 (Pencil & paper)

**Fig. X1-13** Ranked by expertise group (left = high-end, right = low-end)

In Figure X1-13 we show the specific results per expertise group. In X1 the Expert group shows more skills and speed, compared to the Novice and Advanced groups. See Table 1-3 in Appendix A on how the group ranking is achieved. The ranking is based on the iteration time (speed), tacit-tangible skills, and quality of the executed design task. The best individual result was from an expert and the same expert group performed best in total for this X1 test.

## 3.3 Experiment 2 – Sand Sketching

Experiment 2 (X2) is based on soft sand sketching inside a sandbox[2], dimensions 685 x 540 x 20 mm. The box was filled with fine grain white sand (See figure X2-01). A group of 38 individual participants (20 male and 18 female) executed this second test. This X2 group consisted of 68 % BSc. (novice) and 11 % MSc. Students (advanced) in the age of 18-52 years. The final 21 % were expert designers (i.e. lecturers IDE) in the age of 23-56 years. A detailed overview of participants is shown in Table X2-1.

**Table X2-1** Overview participants Experiment 2

| | | | | | | |
|---|---|---|---|---|---|---|
| **Participants X2** | 38 | 20 | 18 | 26 | 4 | 8 |
| (Sand Sketching) | 100 % | 53 % | 47 % | 68 % | 11 % | 21 % |
| | 18-56 years | | | 18-52 years | | 23-56 years |
| | **Total** | **Male** | **Female** | **Novice** | **Advanced** | **Expert** |

### 3.3.1 Typical setup X2

The X2-setup is kept very simple and effective in lay-out. A chair and a table allow the participant to comfortably sit and work during the test. In X2 traditional design tools are provided, such as a pencil, a bamboo pen, and a piece of cardboard as an eraser. A five-minute time limit is set for this experiment. However, in some cases additional time was allowed (Fig. X2-02).

### 3.3.2 Design representation task description X2

The participant is seated during the duration and execution of the test. The facilitator's role is to instruct, observe, and capture the user-interaction (UIA) on video (Fig. 01). The facilitator provides a brief set of instructions and explains the X2 procedure as follows;

- Facilitator shows and hands the A4 to the participant and explains the meaning of the 2-D drawing (Fig. X2-02).
- The design task of X2 is explained to the user.
- The template is placed on the sandbox and explained to the user.
- The facilitator asks consent of the user to capture UIA on video.
- A time constraint of 5 minutes is instructed.
- Start and execution of design task X2.

[2] https://vimeo.com/10382551

**Fig. X2-01** Setup Sand Sketching Bench (X2)

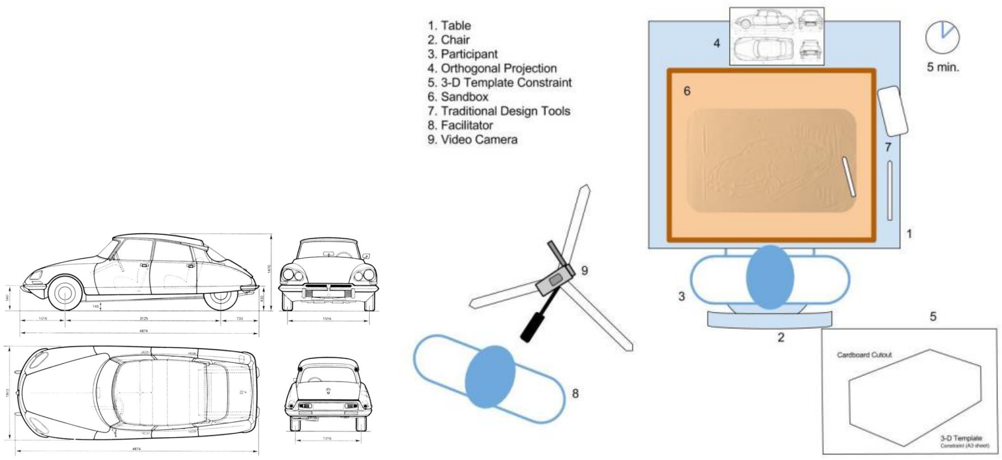



**Fig. X2-02** Orthogonal drawing of a Citroën DS and typical setup X2

### 3.3.3 Representation task X2

Individual participants are asked to interpret and create 3-D sketches based on the artefact (Fig. X2-02). The goal is to 3-D sketch, represent, and interpret as fast as possible the main features and characteristics of the automotive artefact. A perspective template enforcing a size constraint (Fig. X2-03 No. 5 and Fig. X2-03) is used to serve as temporary placeholder. The perspective template provides the participant with an initial direction and position on the sketch-plane. This constraint-based procedure is necessary to be able to compare (rank) the individual sketches, effectiveness and quality of the results after the experimentation concluded.

### 3.3.4 User interaction X2

The designer has to have a good mental image, detailed insight and understanding of the total 'volumetric' shape before commencing with the modelling (Fig. X2-03). Since all the views and elevations merge into one or several fluent and curving lines the shape and form should be clear in advance. To test the methodology in this setup, we observe the effectiveness, ideation skills,

visualization speed, apparent tacit knowing and the threshold in learning. We measure the interpretation in relation to the artefact representation, qualitative results of the individual process outcome with the sketching tool setup in conjunction with the process speed of interaction. We compare all the results from this sketching process and rank (see Table X2-1) them based on the established MQ of Chapter 2.6 (i.e. shape and form vs iteration speed).
During Sand sketching the processing frequently becomes 'hindered' by the randomly moving sand kernels. However, this encouraged faster iteration and intuitive interaction from the participants.

**Fig. X2-03** Start of test procedure participant with sketching constraint marked on sand surface

### 3.3.5 Tangible test results X2 (selection)

In Figure X2-06 to Figure X2-11 a selection of X2- representation results are shown. The presented selection has no particular order or based on qualitative indicators. The images show the variety and diversity in solutions and representational visualizations.

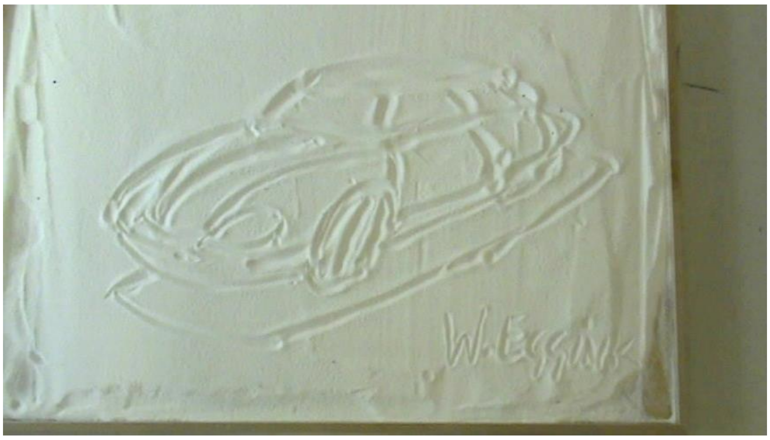


**Fig. X2-04** Sketch participant no. X2-10

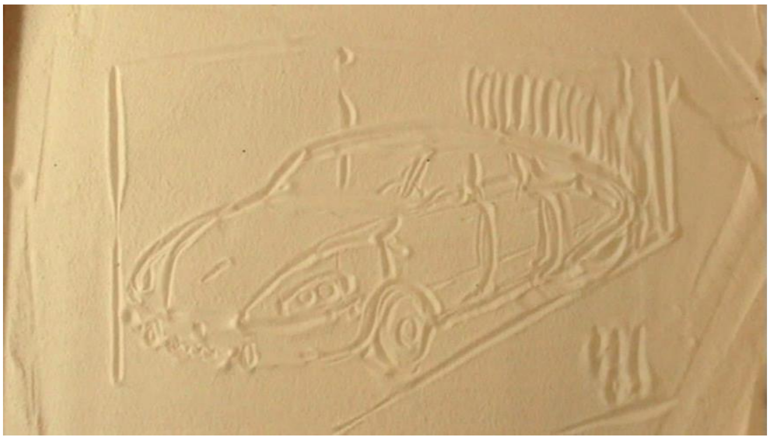


**Fig. X2-05** Sketch participant no. X2-04

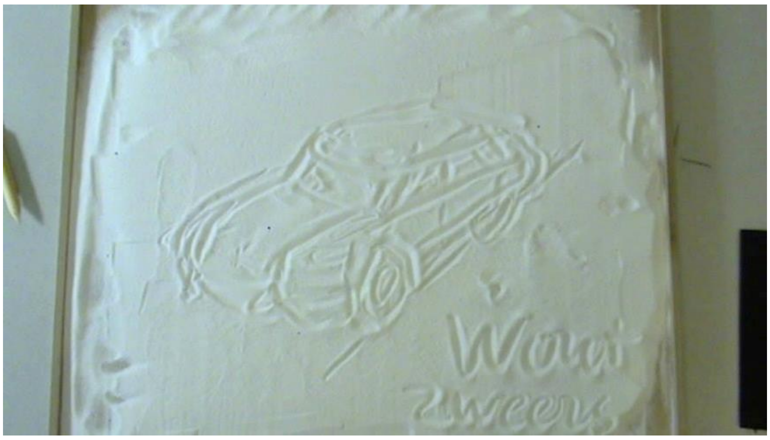


**Fig. X2-06** Sketch participant no. X2-06

**Fig. X2-07** Sketch participant no. X2-02

**Fig. X2-08** Sketch participant no. X2-22

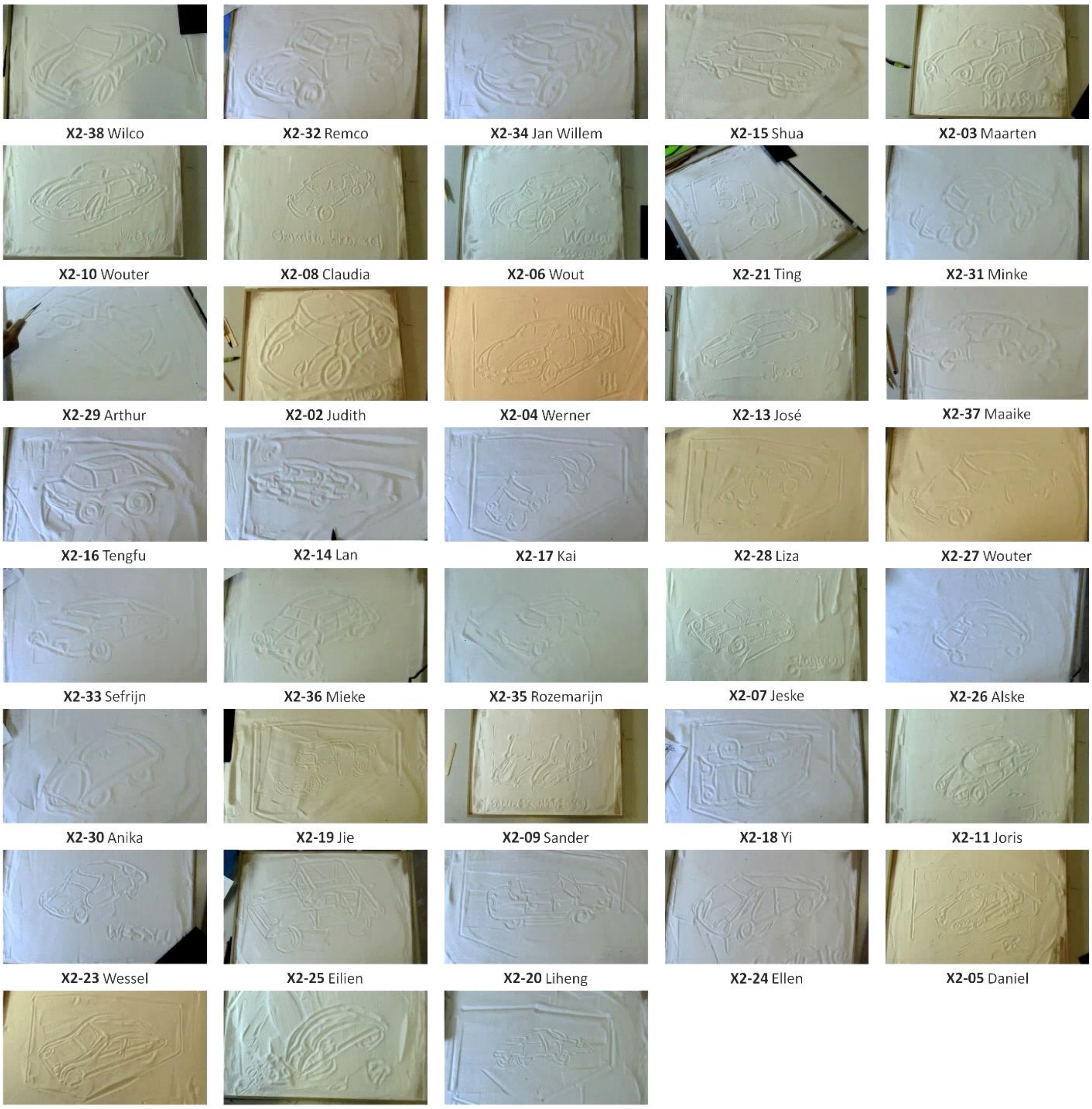
**Fig. X2-09** Sketch participant no. X2-25

For more results of other participants see Table X2-2.

## 3.3.6 Overall ranking results sand sketching test

**Table X2-2** Time & quality combined (left to right - top to bottom)

Left to Right - Top to Bottom (38 results)



**X2-38** Wilco, **X2-32** Remco, **X2-34** Jan Willem, **X2-15** Shua, **X2-03** Maarten

**X2-10** Wouter, **X2-08** Claudia, **X2-06** Wout, **X2-21** Ting, **X2-31** Minke

**X2-29** Arthur, **X2-02** Judith, **X2-04** Werner, **X2-13** José, **X2-37** Maaike

**X2-16** Tengfu, **X2-14** Lan, **X2-17** Kai, **X2-28** Liza, **X2-27** Wouter

**X2-33** Sefrijn, **X2-36** Mieke, **X2-35** Rozemarijn, **X2-07** Jeske, **X2-26** Alske

**X2-30** Anika, **X2-19** Jie, **X2-09** Sander, **X2-18** Yi, **X2-11** Joris

**X2-23** Wessel, **X2-25** Eilien, **X2-20** Liheng, **X2-24** Ellen, **X2-05** Daniel

**X2-01** Sophie, **X2-12** Bas, **X2-22** Xiaogian

## 3.3.7 Analysis and evaluation X2

In figure X2-10 individual iteration and processing time of the 38 participants in X2.

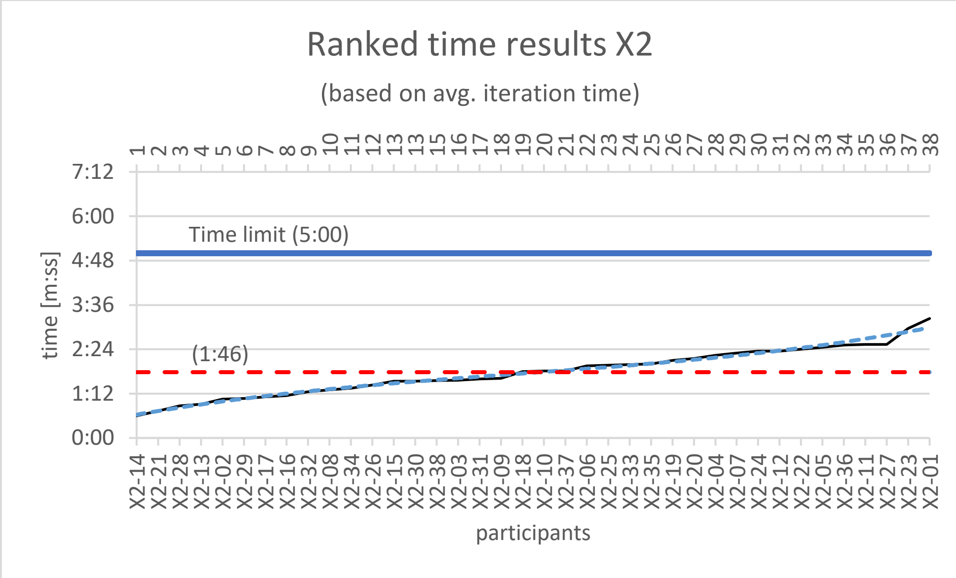



**Fig. X2-10** Ranked by time (left = fast, right = slow)

Presented in Fig. X2-10 are all 38 individual results (black jagged line). A steady curve (3rd order polynomial) trend line (blue dashed curve) results in a CC = 99,3 %. The average iteration time is 1’ 46” (red dash line) which stays well below the 5 minutes time limit.

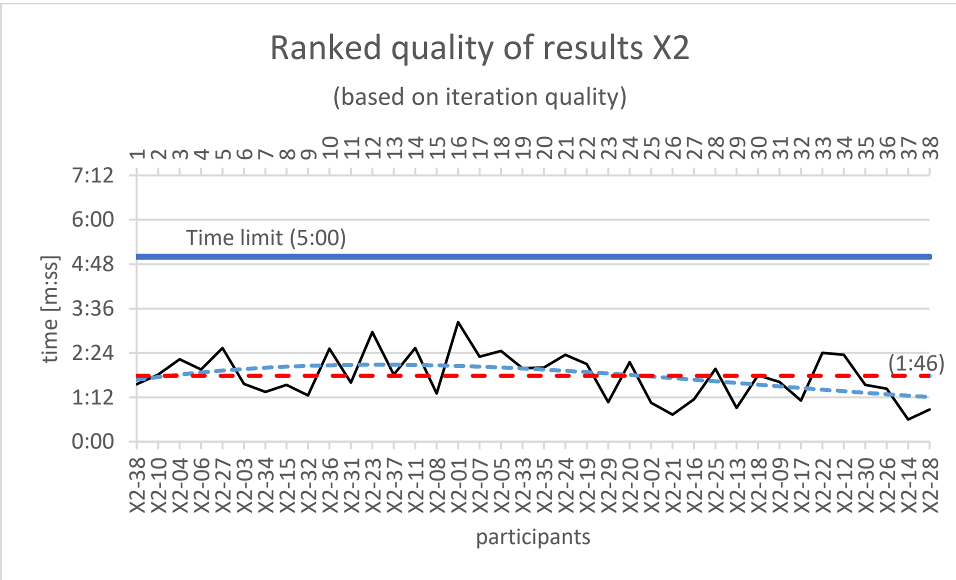



**Fig. X2-11** Ranked by quality (left = good, right = sufficient)

When we display the quality ranked iterations as in Fig. X2-11, the data points get more irregular and jagged (black line). The (3rd order polynomial) trend line (blue dashed line) becomes convex curved with a CC = 43,5 %.

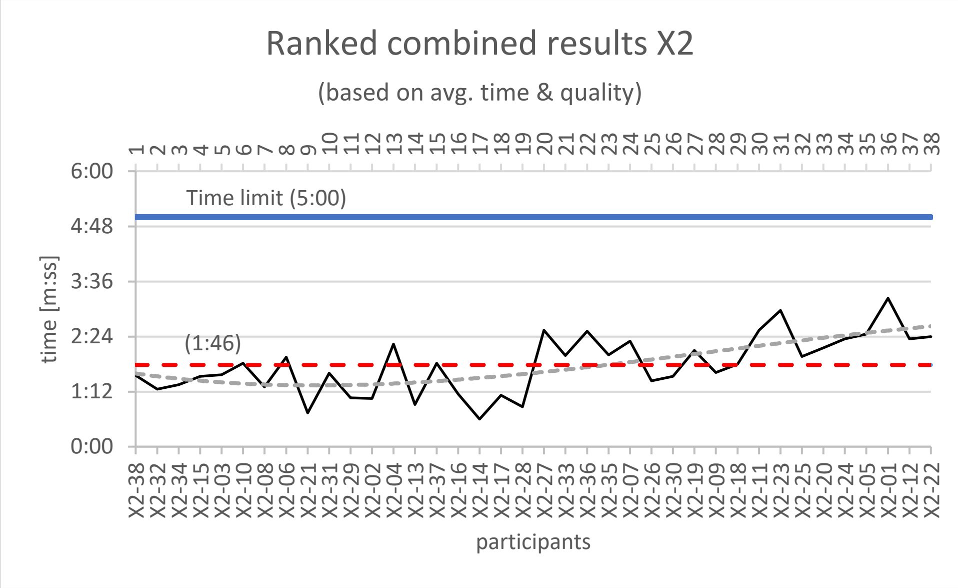
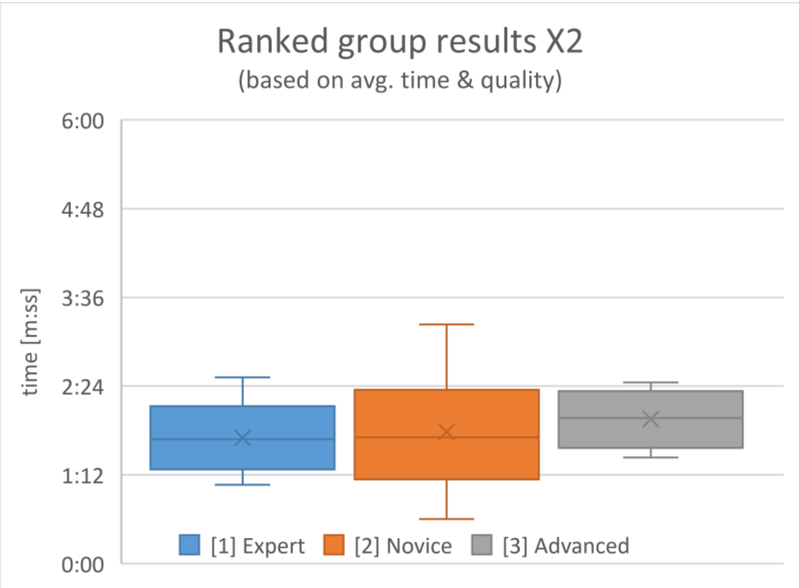



**Fig. X2-12** Ranked by combined results (left = good, right = sufficient)

In Fig. X2-12 we present the individual quality ranked iterations (black jagged line). The data points get more smoothed out and the (3rd order polynomial) trend line X2 (grey undulated dash line) becomes more straight with a CC = 67,6 %.




<u>From left to right</u>

1st Expert X2 (Sand sketching)

2nd Novice X2 (Sand sketching)

3rd Advanced X2 (Sand sketching)

**Fig. X2-13** Ranked by expertise group (left = high-end, right = low-end)

In Figure X2-13 we show the specific results per expertise group. In X2 the Expert group shows more skills and speed, compared to the Novice and Advanced groups. See Table 2-3 in Appendix A on how the group ranking is achieved. The ranking is based on the iteration time (speed), tacit-tangible skills, and quality of the executed design task. The best individual result was from an <u>expert</u> and the same <u>expert group</u> performed best in total for this X2 test.

## 3.4 Experiment 3 - Steam Sketching

Experiment 3 (X3) is based on freehand finger sketching on a fogged-up mirror[3], dimensions 600 x 600 mm. A group of 40 individual participants (21 male and 19 female) executed this third test. This X3 group consisted of 62 % BSc. (novice) and 18 % MSc. students (advanced) in the age of 18-56 years. The final 20 % were expert designers (i.e. lecturers IDE) in the age of 23-56 years. A detailed overview of participants is shown in Table X3-1.

**Table X3-1** Overview participants Experiment 3

| | | | | | | |
|---|---|---|---|---|---|---|
| **Participants X3** (Steam Sketching) | 40 | 21 | 19 | 25 | 7 | 8 |
| | 100 % | 53 % | 47 % | 62 % | 18 % | 20 % |
| | 18-56 years | | | 18-56 years | | 23-56 years |
| | **Total** | **Male** | **Female** | **Novice** | **Advanced** | **Expert** |

### 3.4.1 Typical setup X3

The X3-setup is kept very simple and effective in lay-out (see figure X3-1). A chair and a table allow the participant to comfortably sit and work during the test. In X3 a simple foam-board cut-off 'tools' to sketch on the mirror during the design task. This allowed them to sketch more in detail instead of using their fingers as drawing instrument. A five-minute time limit is set for this experiment. However, in some cases we allowed additional time (Fig. X3-03). This test had to be executed very quickly and with speed in interaction. To make a representation on the mirror covered with steam is a real challenge, because the continuous flow of steam constantly erased the earlier drawing lines. However, this triggered the intuitive interaction and speed of execution. The quality and level of detailing became of less interest, which in turn lead to more iterations over time.

### 3.4.2 Design representation task description X3

The participant is seated during the duration and execution of the test. The facilitator's role is to instruct, observe, and capture the user-interaction (UIA) on video (Fig. X3-01). The facilitator provides a brief set of instructions and explains the X3 procedure as follows;

- Facilitator shows and hands the A4 to the participant and explains the meaning of the 2-D drawing (Fig. X3-02 left)
- The design task of X3 is explained to the user
- No template is being used however the procedure is explained to the user
- The facilitator asks consent of the user to capture UIA on video (Fig. X3-02 No. 9)
- A time constraint of 5 minutes is instructed
- Start and execution of design task X3

[3] https://vimeo.com/10350603

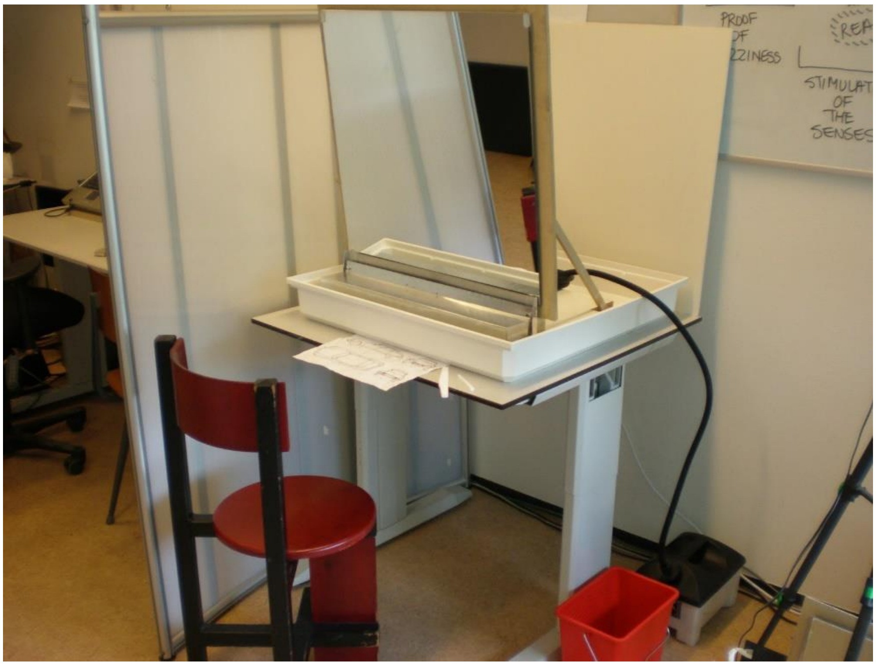


**Fig. X3-01** Setup Steam Sketching bench (X3)

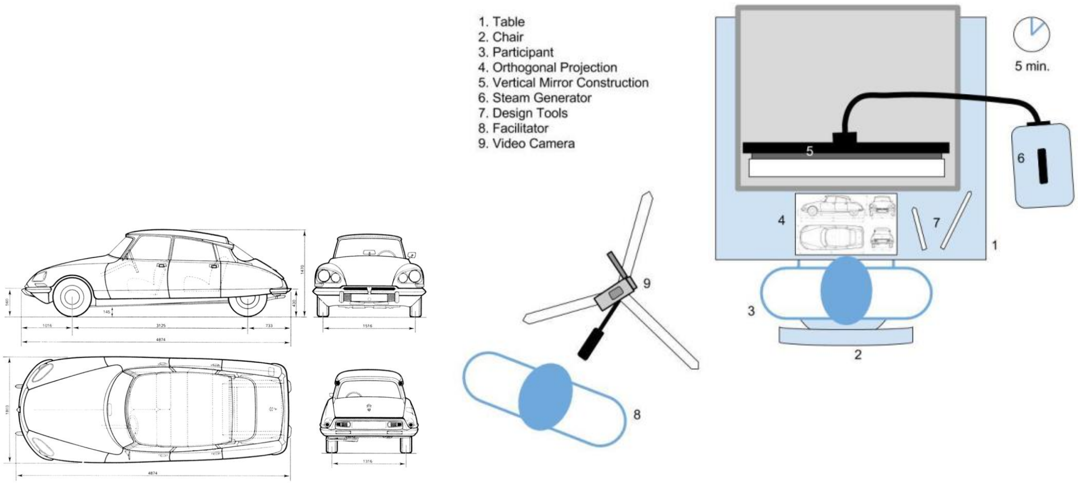


**Fig. X3-02** Orthogonal drawing of a Citroën DS and typical setup X3

### 3.4.3 Representation task X3

Individual participants are asked to interpret and create 3-D sketches based on the artefact (Fig. X3-02 left). The goal is to 3-D sketch, represent, and interpret as fast as possible the main features and characteristics of the automotive artefact.

### 3.4.4 User interaction X3

The designer has to have a good mental image, detailed insight and understanding of the total 'volumetric' shape before commencing with the modelling (Fig. X3-03) Since all the views and elevations merge into one or several fluent and curving lines the shape and form should be clear in advance. To test the methodology in this setup, we observe the effectiveness, ideation skills, visualization speed, apparent tacit knowing and the threshold in learning. We measure the interpretation in relation to the artefact representation, qualitative results of the individual process outcome with the sketching tool setup in conjunction with the process speed of interaction. We

compare all the results from this sketching process and rank (see Table 3-1) them based on the established MQ (i.e. shape and form vs iteration speed).
During the Steam sketching sequence participants are prompted almost immediately into speedy interaction to create their drawings on the fogged-up mirror. This test setup demands speed because of the constant flow of steam over the mirrored surface. The sketches become almost invisible soon after sketching. Thus they stimulate action, fast performance and inspire flow-in-action.

**Fig. X3-03** Start of Test Procedure Participant in front of fogged-up mirror

### 3.4.5 Tangible test results X3 (selection)

In Figure X3-06 to Figure X3-11 a selection of X3- representation results are shown. The presented selection has no particular order or based on qualitative indicators. The images show the variety and diversity in solutions and representational visualizations.

**Fig. X3-04** Sketch participant no. X3-16


**Fig. X3-05** Sketch participant no. X3-40

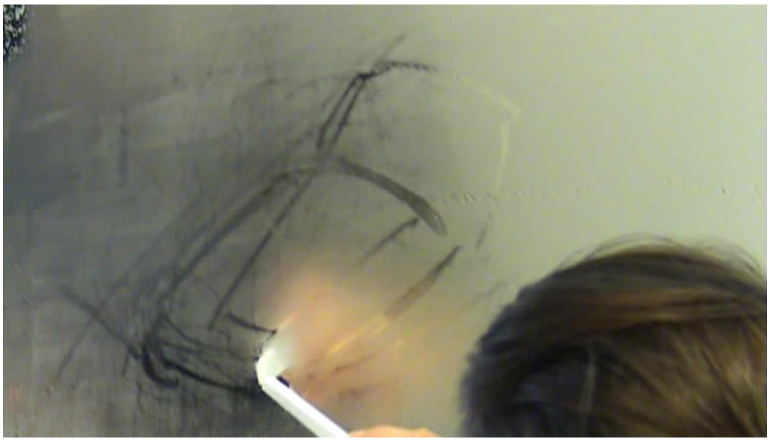


**Fig. X3-06** Sketch participant no. X3-02


**Fig. X3-07** Sketch participant no. X3-22

**Fig. X3-08** Sketch participant no. X3-23

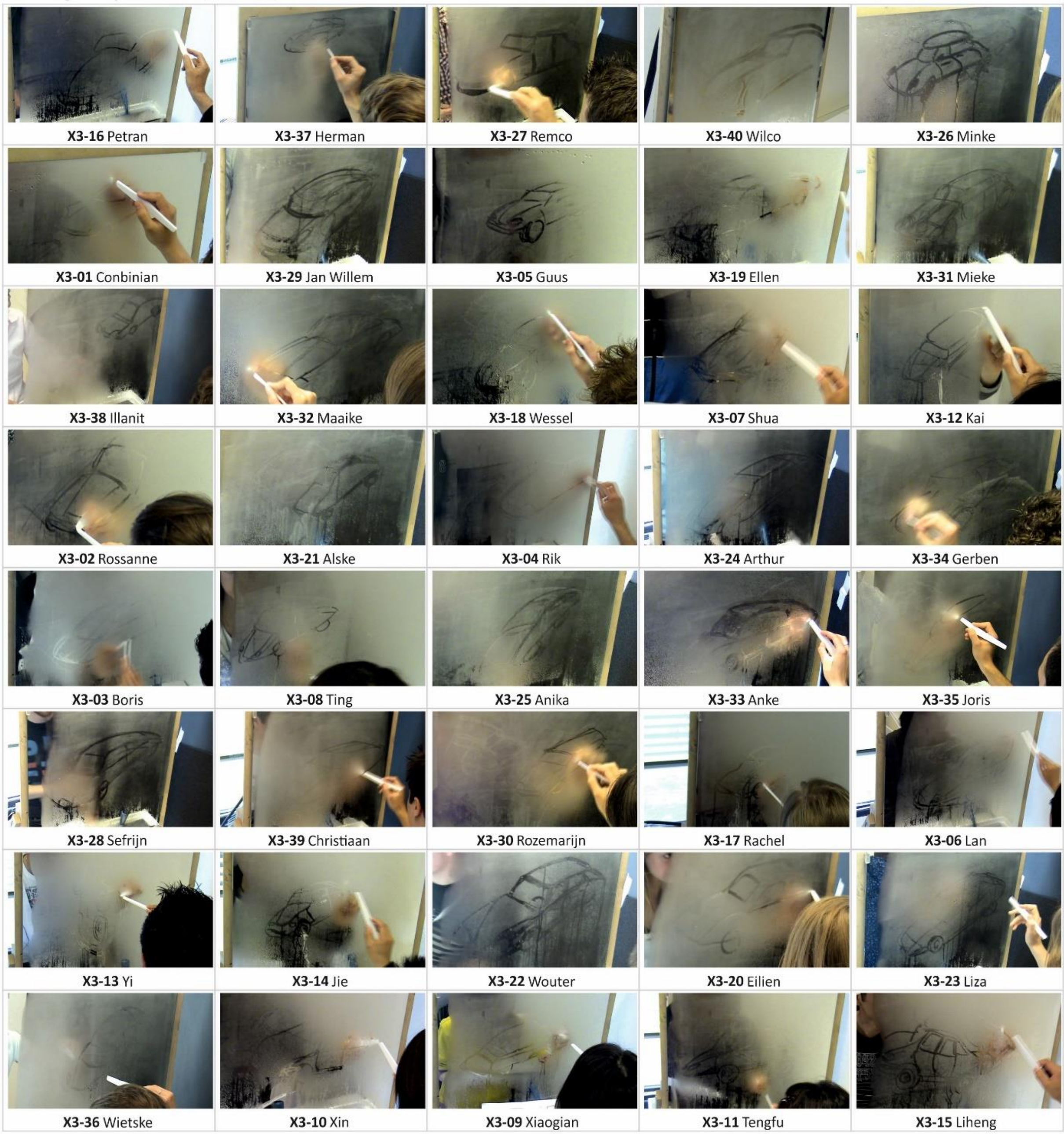
**Fig. X3-09** Sketch participant no. X3-36

For more results of other participants see Table X3-2.

## 3.4.6 Overall ranking results ranking results steam sketching test

**Table X3-2** Time & quality combined (left to right - top to bottom)

Left to Right - Top to Bottom (40 results)




## 3.4.7 Analysis and evaluation X3

In figure X3-12 individual iteration and processing time of the 40 participants in X3 are presented.

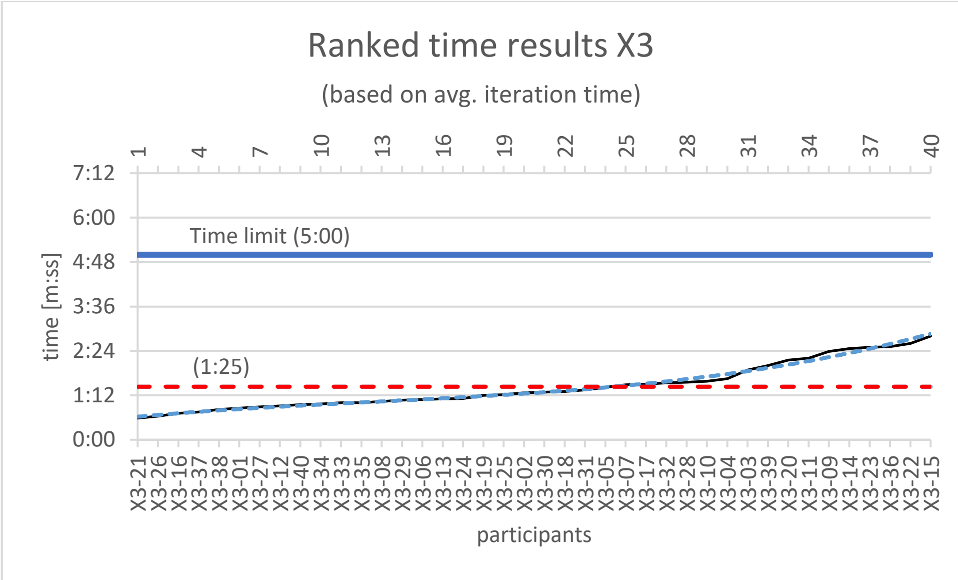



**Fig. X3-10** Ranked by time (left = fast, right = slow)

Presented in Fig. X3-10 are all 40 individual results (black jagged line). A steady curve (3rd order polynomial) trend line (blue dashed curve) results in a CC = 99,5 %. The average iteration time is 1’ 25” (red dash line) which stays well below the 5 minutes time limit.

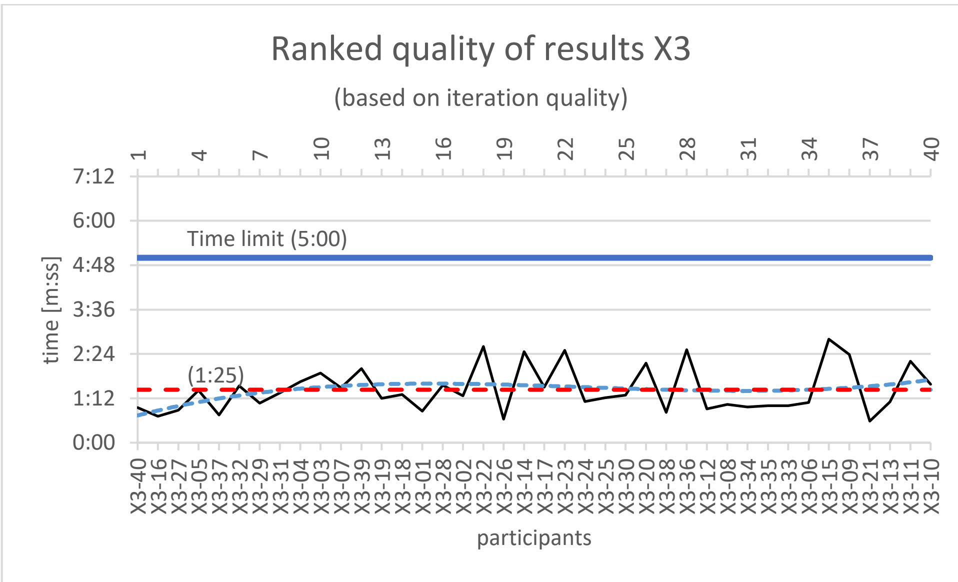



**Fig. X3-11** Ranked by quality (left = good, right = sufficient)

When we display the quality ranked iterations as in Fig. X3-11, the data points get more irregular and jagged (black line). The (3rd order polynomial) trend line (blue dashed line) becomes convex curved with a CC = 33,0 %.

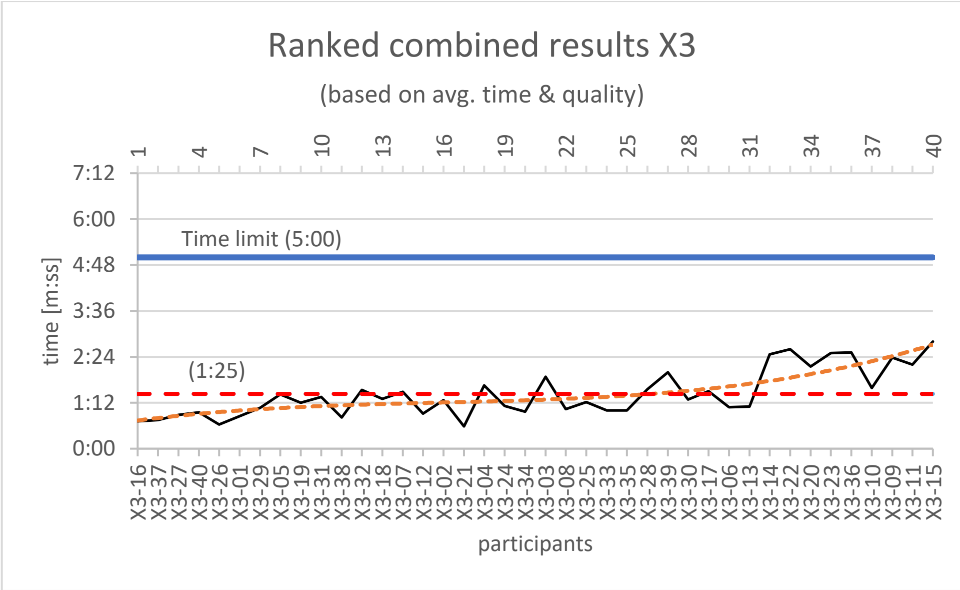
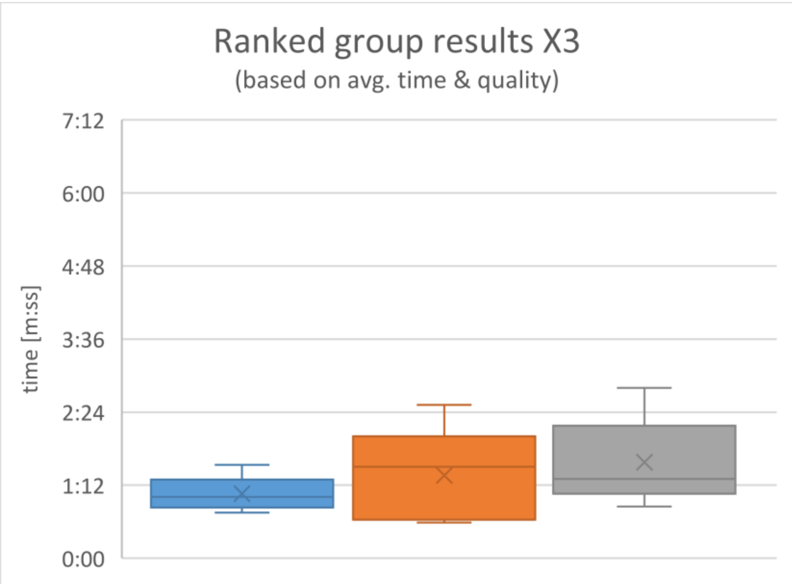



**Fig. X3-12** Ranked by combined results (left = good, right = sufficient)

In Fig. X3-12 we present the individual quality ranked iterations (black jagged line). The data points get more smoothed out and the (3rd order polynomial) trend line X3 (orange undulated dash line) becomes more straight with a CC = 80,0 %.




<u>From left to right</u>

1st Expert X3 (Steam sketching)

2nd Advanced X3 (Steam sketching)

3rd Novice X3 (Steam sketching)

**Fig. X3-13** Ranked by expertise group (left = high-end, right = low-end)

In Figure X3-13 we show the specific results per expertise group. In X3 the Expert group shows more skills and speed, compared to the Novice and Advanced groups. See Table 3-3 in Appendix A on how the group ranking is achieved. The ranking is based on the iteration time (speed), tacit-tangible skills, and quality of the executed design task. The best individual result was from an <u>advanced</u>, while the <u>expert group</u> performed best in total for this X3 test.

## 3.5 Experiment 4 – (3-D) Sand Sculpting

Experiment 4 (X4) is based on free-hand sculpting with a formable sand-mass in a sandbox[4], dimensions 685 x 540 x 20 mm. A group of 34 individual participants (16 male and 18 female) executed this fourth test. This X4 group consisted of 56 % BSc. (novice) and 21 % MSc. students (advanced) in the age of 18-56 years. The final 23 % were expert designers (i.e. lecturers IDE) in the age of 23-56 years. A detailed overview of participants is shown in Table X4-1.

**Table X4-1** Overview participants Experiment 4

| | | | | | | |
|---|---|---|---|---|---|---|
| **Participants X4** | 34 | 16 | 18 | 19 | 7 | 8 |
| (Sand Sculpting) | 100 % | 47 % | 53 % | 56 % | 21 % | 23 % |
| | 18-56 years | | | 18-56 years | | 23-56 years |
| | **Total** | **Male** | **Female** | **Novice** | **Advanced** | **Expert** |

### 3.5.1 Typical setup X4

The X4-setup is kept very simple and effective in lay-out. A chair and a table allow the participant to comfortably sit and work during the test. In X4 both hands are used in this combination with traditional design tools are provided, such as spatula, bamboo-pen and a flat piece of wood. A five-minute time limit is set for this experiment. However, in some cases additional time was allowed (Fig. X4-03).

### 3.5.2 Design representation task description X4

The participant is seated during the duration and execution of the test. The facilitator's role is to instruct, observe, and capture the user-interaction (UIA) on video (Fig. X4-01). The facilitator provides a brief set of instructions and explains the X4 procedure as follows;

- Facilitator shows and hands the A4 to the participant and explains the meaning of the 2-D drawing (Fig. X4-02 left)
- The design task of X4 is explained to the user
- No template is used during this experiment
- The facilitator asks consent of the user to capture UIA on video (Fig. X4-02 No. 9)
- A time constraint of 5 minutes is instructed
- Start and execution of design task X4

[4] https://vimeo.com/10351035

**Fig. X4-01** Setup Sand Sculpting test bench (X4)

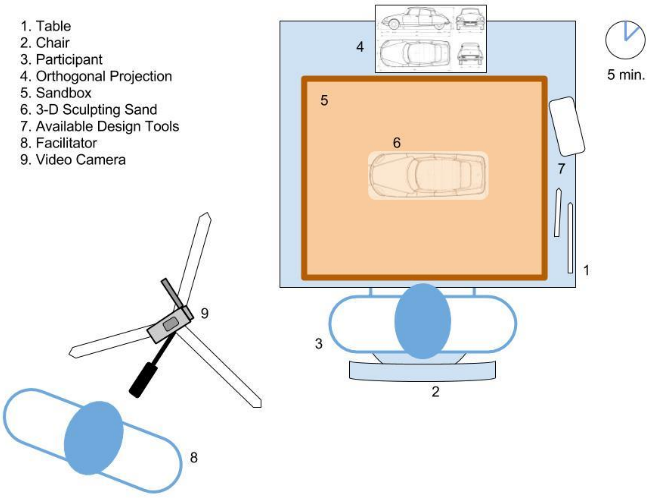



**Fig. X4-02** Diagram of setup X4

## 3.5.3 Representation task X4

Individual participants are asked to interpret and create 3-D sculptures based on the orthogonal drawing of the artefact (Fig. X4-02). The goal is to 3-D sketch, represent, and interpret as fast as possible the main features and characteristics of the automotive artefact in formable sand mass.

## 3.5.4 User interaction X4

The designer has to have a good mental image, detailed insight and understanding of the total ‘volumetric’ shape before commencing with the modelling (Fig. X4-03). Since all the views and elevations merge into one or several fluent and curving lines the shape and form should be clear in advance. ’Distortions in the visual perception of three-dimensional form can be corrected by tactile observations’ (ibid. W. Gilles, 1991). To test the methodology in this setup, we observe the effectiveness, ideation skills, visualization speed, apparent tacit knowing and the threshold in learning.

We measure the interpretation in relation to the artefact representation, qualitative results of the individual process outcome with the sketching tool setup in conjunction with the process speed of interaction. We compare all the results from this sketching process and rank (see Table 04-1) them based on the established MQ (i.e. shape and form vs iteration speed).

The two-handed Sculpting test bench maximizes the tangible-tactile experience of the participant. The formable mass (form-sand) allows for fast and speedy iterations and stimulates the haptic senses, manual dexterity, touch receptors and sensorial imagination. Some wooden tools are being used during processing to allow the introduction of some detailing (Fig. X4-03).

**Fig. X4-03** Start of test procedure participant with formable mass in sandbox.

### 3.5.5 Tangible test results X4 (selection)

In Figure X4-06 to Figure X4-11 a selection of X4-representation results are shown. The presented selection has no particular order or based on qualitative indicators. The images show the variety and diversity in solutions and representational visualizations.

**Fig. X4-04** Sand Sculpting participant no. X4-05

**Fig. X4-05** Sand Sculpting participant no. X4-17

**Fig. X4-06** Sand Sculpting participant no. X4-22

**Fig. X4-07** Sand Sculpting participant no. X4-32

**Fig. X4-08** Sand Sculpting participant no. X4-24

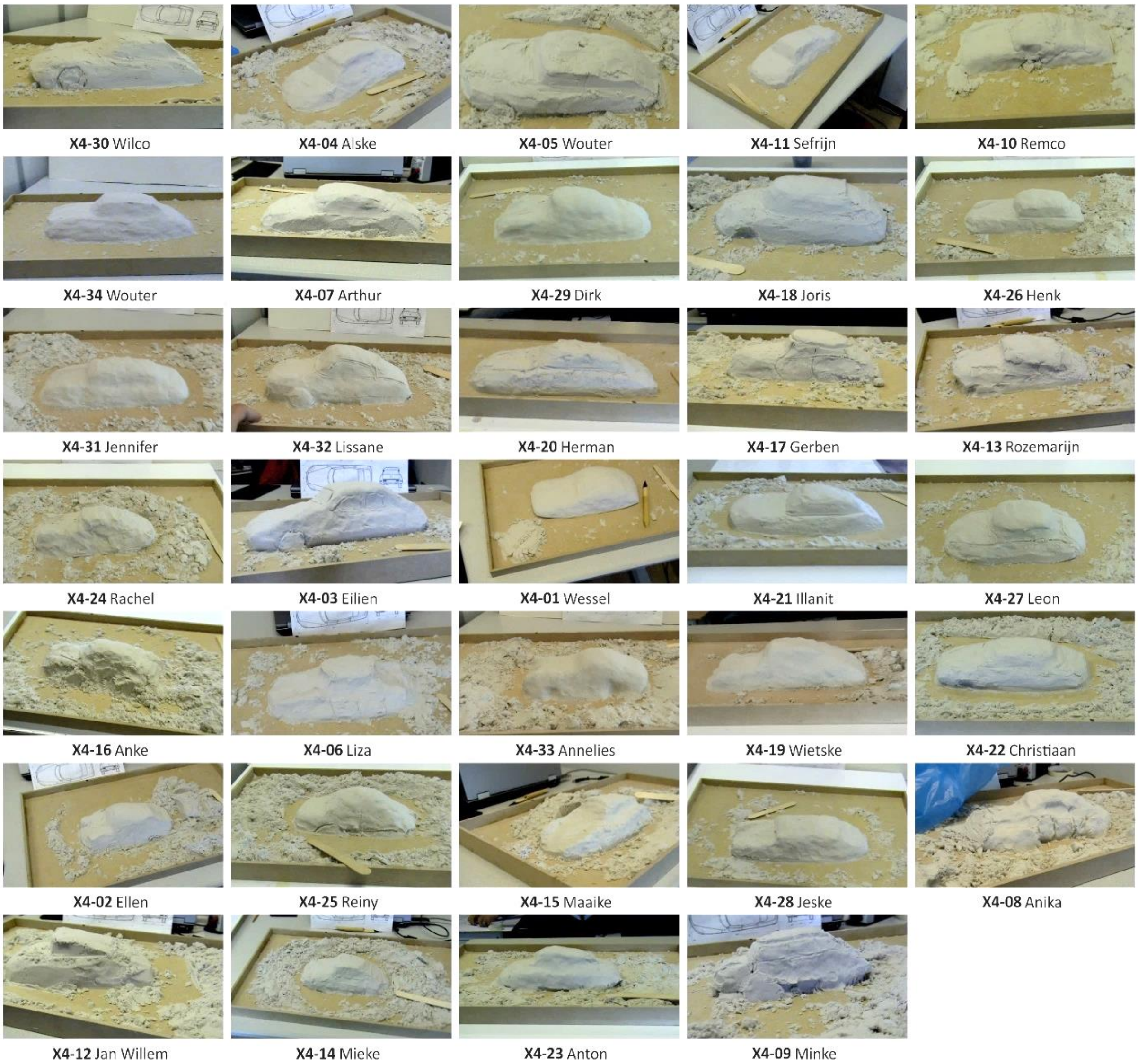
**Fig. X4-09** Sand Sculpting participant no. X4-16

For more results of other participants see Table X4-2.

### 3.5.6 Overall ranking results sand sculpting test

**Table X4-2** Time & quality combined (left to right - top to bottom)

Left to Right - Top to Bottom (34 results)




### 3.5.7 Analysis and Evaluation X4

In figure X4-12 shown are the individual iteration and processing time of the 34 participants in X4.

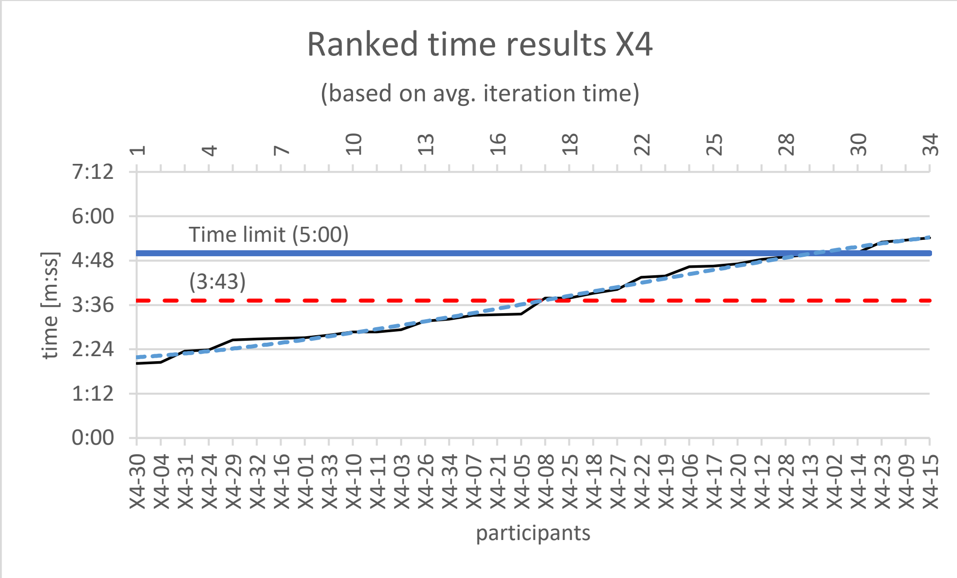



**Fig. X4-10** Ranked by time (left = fast, right = slow)

Presented in Fig. X4-10 are all 34 individual results (black jagged line). A steady curve (3rd order polynomial) trend line (blue dashed line) results in a CC = 99,4 %. The average iteration time is 3' 43" (red dash line) which stays well below the 5 minutes time limit.

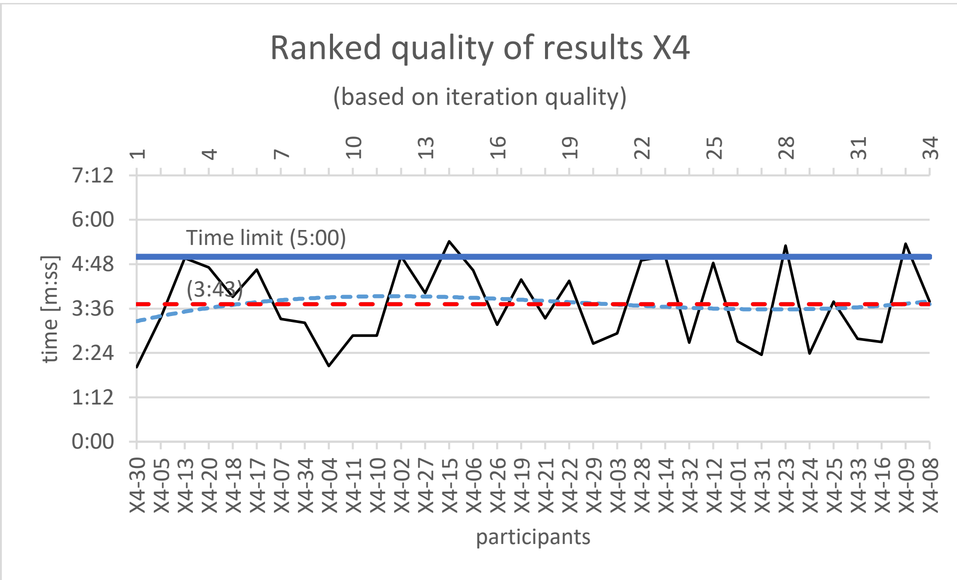



**Fig. X4-11** Ranked by quality (left = good, right = sufficient)

When we display the quality ranked iterations as in Fig. X4-11, the data points get more irregular and jagged (black line). The (3rd order polynomial) trend line (blue dashed line) becomes convex curved with a CC = 15,3 %.

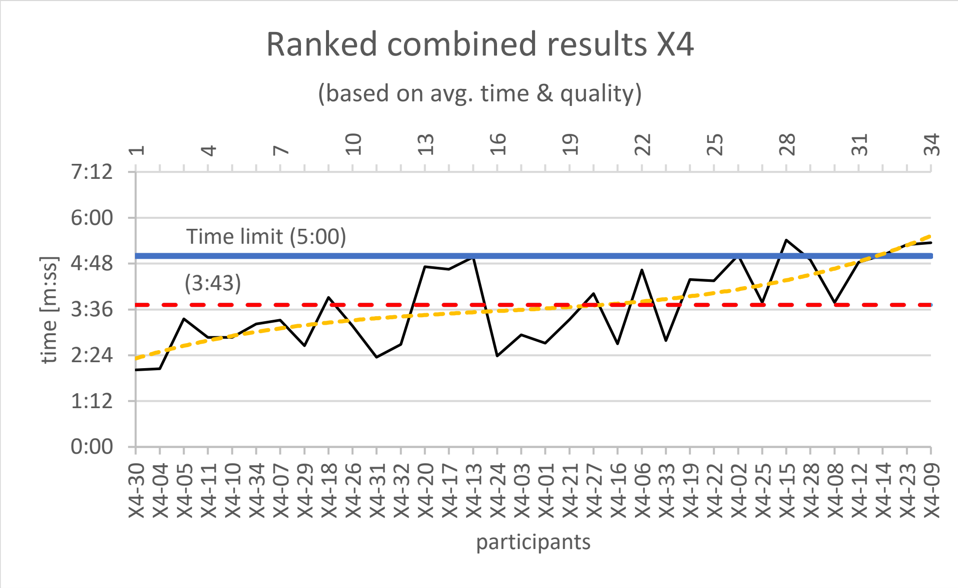
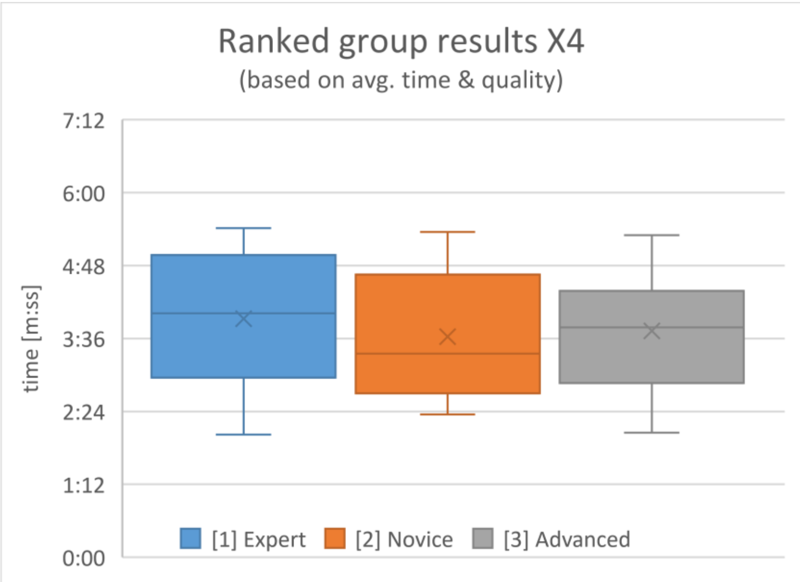



**Fig. X4-12** Ranked by combined results (left = good, right = sufficient)

In Fig. X4-12 we present the individual quality ranked iterations (black jagged line). The data points get more smoothed out and the (3rd order polynomial) trend line X4 (yellow undulated dash line) becomes more straight with a CC = 72,6 %.




From left to right

1st Expert X4 (Sand sculpting)

2nd Novice X4 (Sand sculpting)

3rd Advanced X4 (Sand sculpting)

**Fig. X4-13** Ranked by expertise group (left = high-end, right = low-end)

In Figure X4-13 we show the specific results per expertise group. In X4 the Expert group shows more skills and speed, compared to the Novice and Advanced groups. See Table 4-3 in Appendix A on how the group ranking is achieved. The ranking is based on the iteration time (speed), tacit-tangible skills, and quality of the executed design task. The best individual result was from an expert and the same expert group performed best in total for this X4 test.

## 3.6 Experiment 5 – Wire Plying (3-D)

Experiment 5 (X5) is based on plying and bending aluminium wire (ø 3.0 mm) to create a 3-D wireframe.[5] A group of 28 individual participants (16 male and 12 female) executed this first test. This X5 group consisted of 64 % BSc. (novice) and 25 % MSc. Students (advanced) in the age of 18-56 years. The final 11 % were expert designers (i.e. lecturers IDE) in the age of 23-36 years. A detailed overview of participants is shown in Table X5-1.

**Table X5-1** Overview participants Experiment 5

| | | | | | | |
|---|---|---|---|---|---|---|
| **Participants X5** | 28 | 16 | 12 | 18 | 7 | 3 |
| (Wire Plying) | 100 % | 57 % | 43 % | 64 % | 25 % | 11 % |
| | 18-56 years | | | 18-56 years | | 23-36 years |
| | **Total** | **Male** | **Female** | **Novice** | **Advanced** | **Expert** |

### 3.6.1 Typical setup X5

The X5-setup is kept very simple and effective in lay-out. A chair and a table allow the participant to comfortably sit and work during the test. In X5 basic design tools are provided, such as pliers and cutter and a roll of masking tape. A five-minute time limit is set for this experiment. However, in some cases we allowed additional time (Fig. X5-02).

### 3.6.2 Design representation task description X5

The participant is seated during the duration and execution of the test. The facilitator's role is to instruct, observe, and capture the user-interaction (UIA) on video (Fig. X5-02). The facilitator provides a brief set of instructions and explains the X4 procedure as follows;

- An enlarged 2-d representation (920 x 630mm) of the orthogonal drawing of a Citroën DS is placed on the table to function as a guiding template
- The design task of X5 is explained to the user
- The procedure is explained to the user
- The facilitator asks consent of the user to capture UIA on video (Fig. X5-02 No. 8)
- A time constraint of 5 minutes is instructed
- Start and execution of design task X5

[5] https://vimeo.com/10382683

**Fig. X5-01** Setup Wire Plying bench (X5)

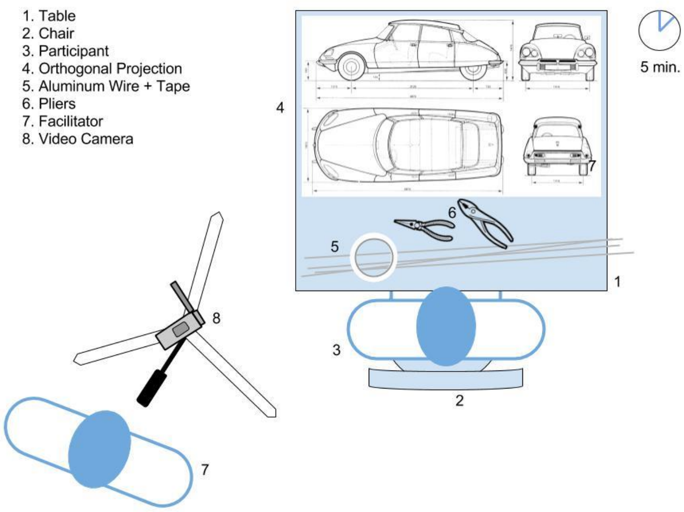



**Fig. X5-02** Diagram of Setup X5

### 3.6.3 Representation task X5

Individual participants are asked to interpret and create 3-D sketches based on the guiding template of the artefact (Fig. X5-01 and Fig. X5-02). The goal is to 3-D sketch, represent, and interpret as fast as possible the main features and characteristics of the automotive artefact. This constraint-based (i.e. based on guiding template) procedure is necessary to be able to compare (rank) the individual sketches, effectiveness and quality of the results after the experimentation concluded.

### 3.6.4 User interaction X5

The designer has to have a good mental image, detailed insight and understanding of the total 'volumetric' shape before commencing with the modelling (Fig. X5-01). Since all the views and elevations merge into one or several fluent and curving lines the shape and form should be clear in advance. Again, 'distortions in the visual perception of three-dimensional form can be corrected by tactile observations' (ibid. W. Gilles, 1991). The Wire Plying test bench is based on two-handed interaction and freeform plying in aluminium wire. The participant has to create a 3-D wire frame of an artefact shown in a set of orthogonal drawings. The use of tape, pliers and wire cutters is allowed. The transformation of the 2-D projections into 3-D tangible wire frames brings out tacit knowing and enhances skill, touch, and choice architecture. The template was enlarged to ease the design task for the participants in this way they could directly translate and transform the aluminium wires to required scale of the wireframe model. To test the methodology in this setup, we observe the effectiveness, ideation skills, visualization speed, apparent tacit knowing and the threshold in learning. We measure the interpretation in relation to the artefact representation, qualitative results of the individual process outcome with the sketching tool setup in conjunction with the process speed of interaction. We compare all the results from this sketching process and rank (see Table. X5-1) them based on the established MQ (i.e. shape and form vs iteration speed).

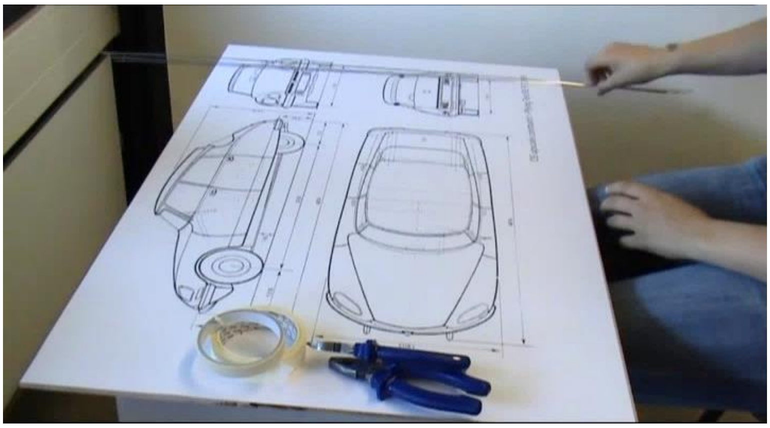


**Fig. X5-03** Start of test procedure participant with enlarged modelling constraint

### 3.6.5 Tangible test results X5 (selection)

In Figure X5-06 to Figure 11 a selection of X2- representation results are shown. The presented selection has no particular order or based on qualitative indicators. The images show the variety and diversity in solutions and representational visualizations.

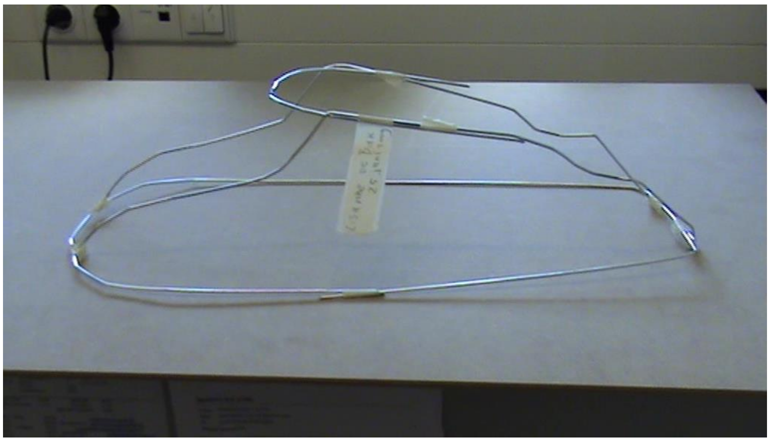


**Fig. X5-04** Wire frame participant no. X5-27

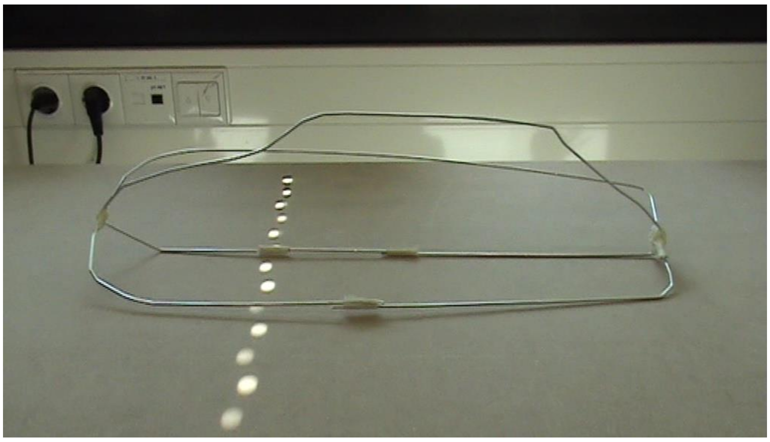


**Fig. X5-05** Wire frame participant no. X5-20

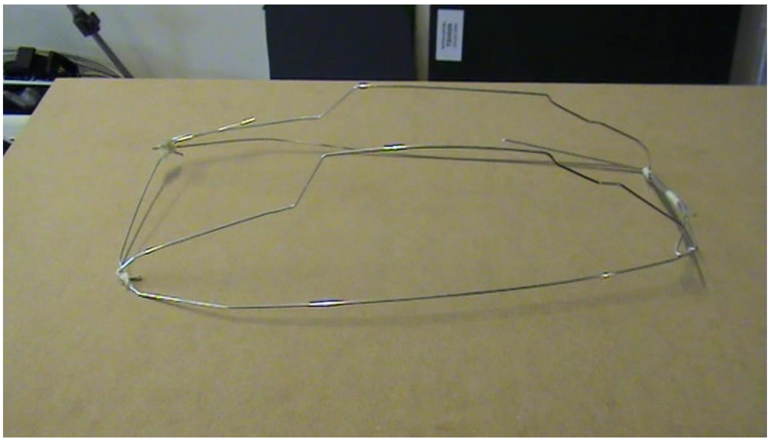


**Fig. X5-06** Wire frame participant no. X5-05

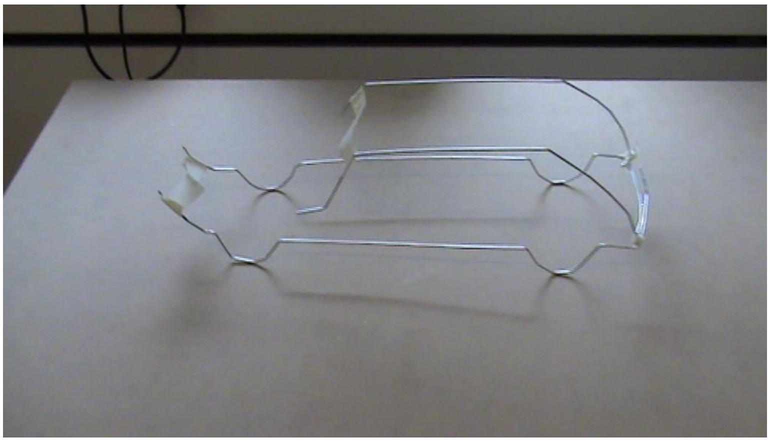


**Fig. X5-07** Wire frame participant no. X5-11

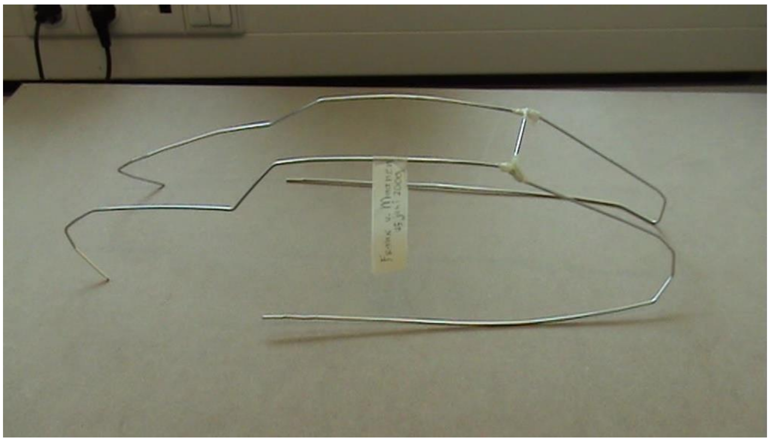


**Fig. X5-08** Wire frame participant no. X5-24

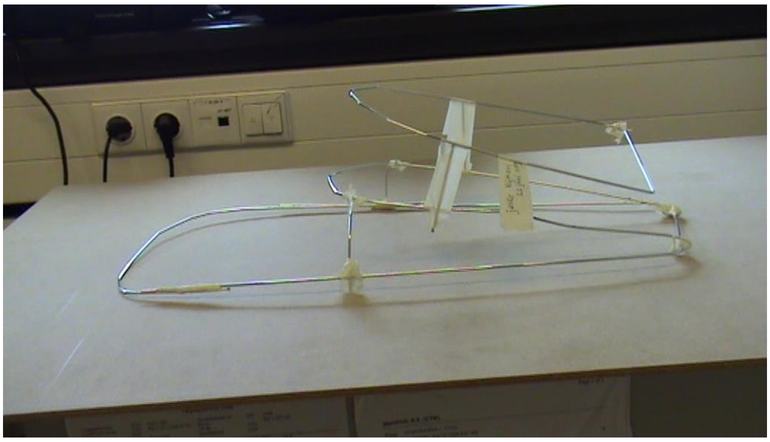


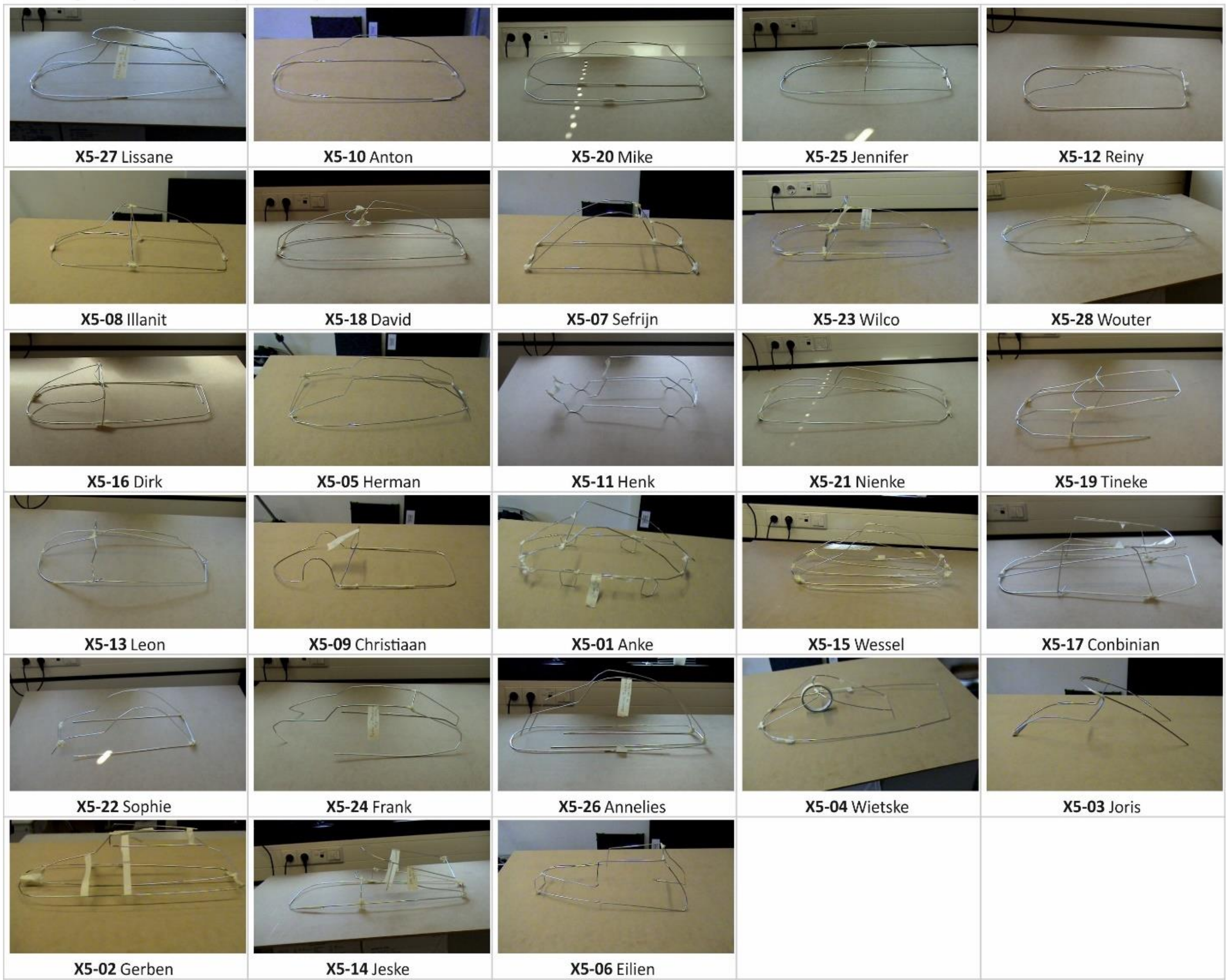
**Fig. X5-09** Wire frame participant no. X5-06

For more results of other participants see Table X5-2.

## 3.6.6 Overall ranking results wire plying test (3-D)

**Table X5-2** Time & quality combined (left to right - top to bottom)

Left to Right - Top to Bottom (28 results)




## 3.6.7 Analysis and evaluation X5

In figure X5-12 individual iteration and processing time of the 28 participants in X5 are presented.

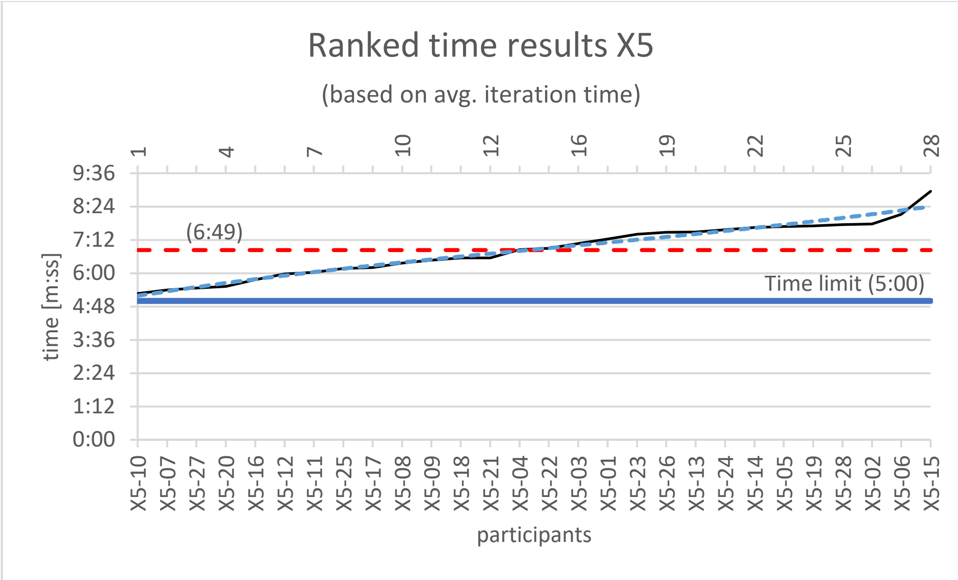



**Fig. X5-10** Ranked by time (left = fast, right = slow)

Presented in Fig. X5-10 are all 28 individual results (black jagged line). A steady upward curve (3rd order polynomial) trend line (blue dashed line) results in a CC = 98,5 %. The average iteration time is 6’ 49” (red dash line) which exceeds the 5 minutes time limit.

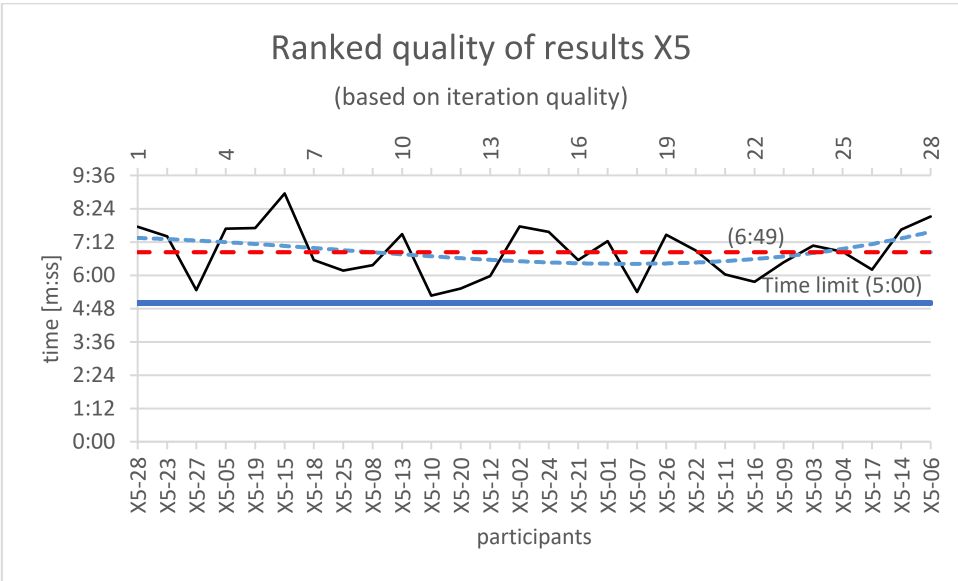



**Fig. X5-11** Ranked by quality (left = good, right = sufficient)

When we display the quality ranked iterations as in Fig. X5-11, the data points get more irregular and jagged (black line). The (3rd order polynomial) trend line (blue dashed line) becomes convex curved with a CC = 36,8 %.

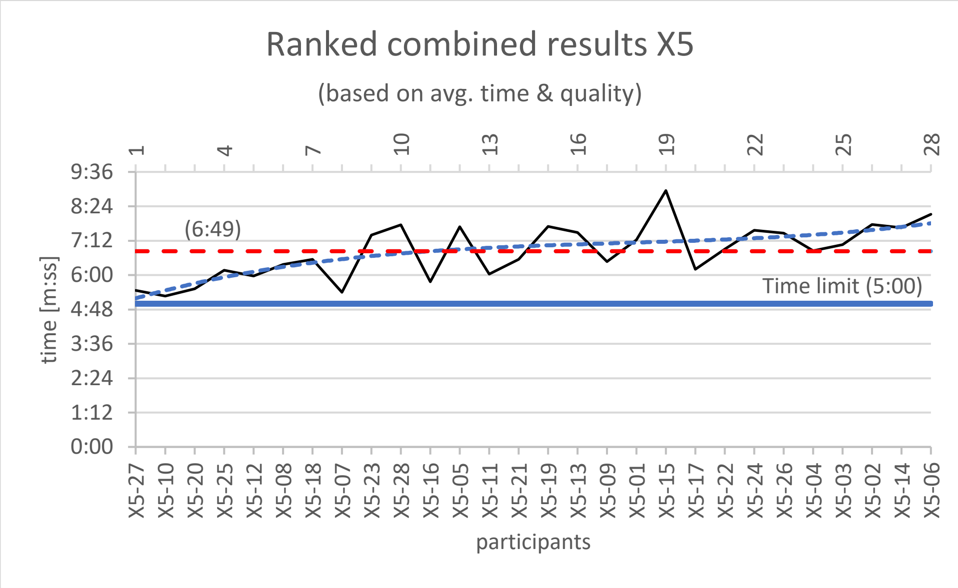
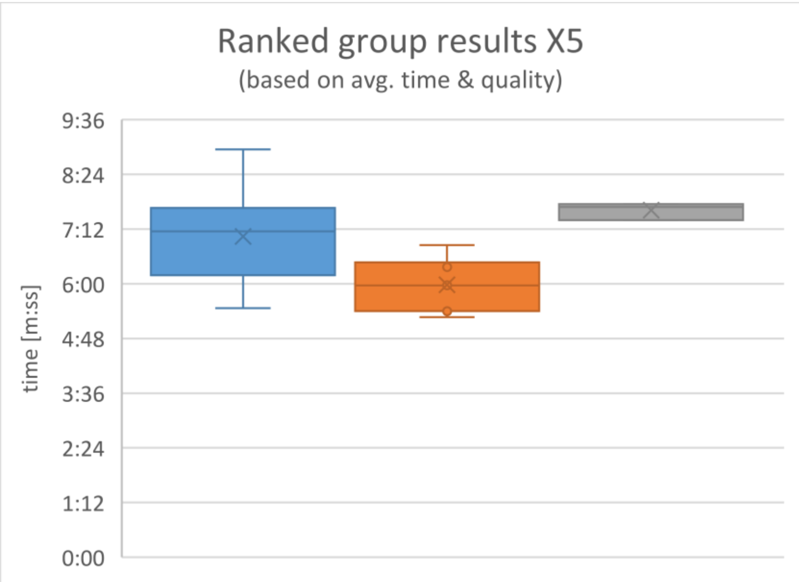



**Fig. X5-12** Ranked by combined results (left = good, right = sufficient)

In Fig. X5-12 we present the individual quality ranked iterations (black jagged line). The data points get more smoothed out and the (3rd order polynomial) trend line X5 (dark blue undulated dash line) becomes more straight with a CC = 70,7 %.




From left to right

1st Novice X5 (Wire plying)

2nd Advanced X5 (Wire plying)

3rd Expert X5 (Wire plying)

**Fig. X5-13** Ranked by expertise group (left = high-end, right = low-end)

In Figure X5-13 we show the specific results per expertise group. In X5 the Novice group shows more skills and speed, compared to the Advanced and Experts groups. See Table 5-3 in Appendix A on how the group ranking is achieved. The ranking is based on the iteration time (speed), tacit-tangible skills, and quality of the executed design task. The best individual result was from a novice and the same novice group performed best in total for this X5 test.

## 3.7 Experiment 6 – 3-D CAD Solid Works

Experiment 6 (X6) is based on computer-aided drawing / design (CAD) with in conjunction with a mouse and keyboard.[6] In this case we used SolidWorks (SW) 3-D CAD software application, version SW2008. A group of 25 individual participants (19 male and 6 female) executed this sixth test. This X6 group consisted of 54 % BSc. (novice) and 23 % MSc. students (advanced) in the age of 18-52 years. The final 23 % were expert designers (i.e. lecturers IDE) in the age of 23-56 years.  A detailed overview of participants is shown in Table X6-1.

**Table X6-1** Overview participants Experiment 6

| | | | | | | |
|---|---|---|---|---|---|---|
| **Participants X6** (3-D CAD SW) | 25 | 19 | 6 | 12 | 5 | 5 |
| | 100 % | 76 % | 24 % | 54 % | 23 % | 23 % |
| | 18-56 years | | | 18-52 years | | 23-56 years |
| | **Total** | **Male** | **Female** | **Novice** | **Advanced** | **Expert** |

### 3.7.1 Typical setup X6

The X6-setup is kept very simple and effective in lay-out. A chair and a table allow the participant to comfortably sit and work during the test. In X6 a generic Windows laptop (OS-Win Vista) configured with the SW-application was facilitated. A five-minute time limit is set for this experiment. However, in some cases we allowed additional time (Fig. X6-02).

### 3.7.2 Design representation task description X6

The participant is seated during the duration and execution of the test. The facilitator's role is to instruct, observe, and capture the user-interaction (UIA) on video (Fig. X6-01).  The facilitator provides a brief set of instructions and explains the X6 procedure as follows;

- We facilitated a 3-D bounding-box with orthogonal elevations in the SW workspace (see Figure X6-01)
- In addition, the 2-D A4 orthogonal projection was provided (Fig. X6-02 No. 4)
- The design task and procedure of X6 is explained to the user
- The facilitator asks consent of the user to capture UIA on video (Fig. X6-02 No. 8)
- A time constraint of 5 minutes is instructed, however right from the start it became clear that an additional 5-10 minutes were required to obtain 'tangible' results
- Start and execution of design task X6

[6] https://vimeo.com/10351195

**Fig. X6-01** Setup 3-D Solid Works bench (X6)

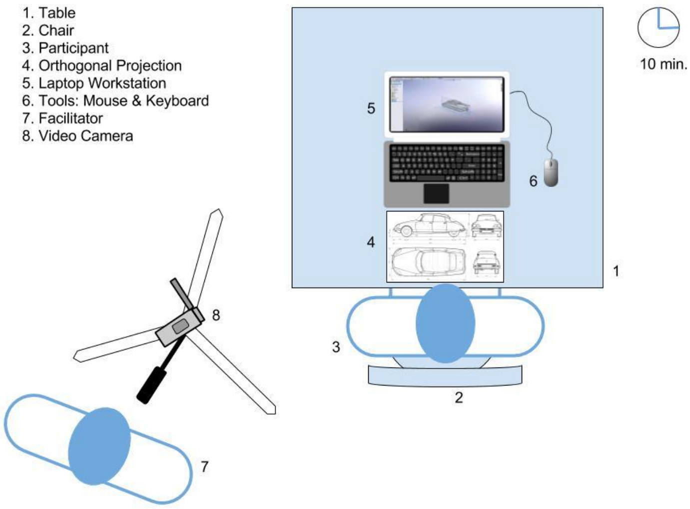



**Fig. X6-02** Diagram of setup X6

### 3.7.3 Representation task X6

Individual participants are asked to interpret and create 3-D CAD sketch/draw models based on the representation of the artefact in the 3-D size constraint bounding box (Fig. X6-01). To lower the threshold in learning we provided this three-dimensional workspace including views and elevations of the artefact. In addition, the 2-D orthogonal drawing of the artefact is supplied as source of reference. The goal is to 3-D create, represent, and interpret as fast as possible the main features and characteristics of the automotive artefact. This constraint-based procedure is necessary to be able to compare (rank) the individual sketches, effectiveness and quality of the results after the experimentation concluded.

### 3.7.4 User interaction X6

The designer has to have a good mental image, detailed insight and understanding of the total 'volumetric' shape before commencing with the modelling (Fig. X6-01 and Fig. X6-03). Since all the views and elevations merge into one or several fluent and curving lines the shape and form should be clear in advance to the participant. This way a mental model of the volumetric shape, form and proportions will assist the participant in recreating a 3-D virtual model. To test the methodology in this setup, we observe the effectiveness, ideation skills, visualization speed, apparent tacit knowing and the threshold in learning. We measure the interpretation in relation to the artefact representation, qualitative results of the individual process outcome with the sketching tool setup in conjunction with the process speed of interaction. We compare all the results from this 3-D CAD sketch/draw process and rank (see Table X6-1) them based on the established MQ (i.e. shape and form vs iteration speed).

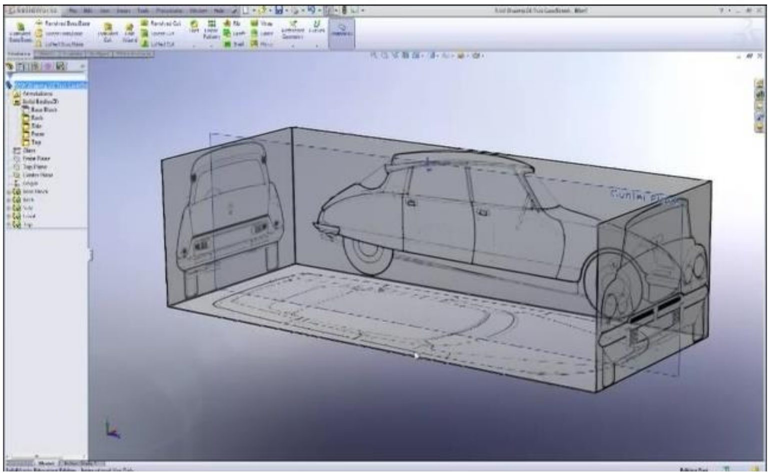


**Fig. X6-03** Start of test procedure participant with 3-D modelling constraint in SW workspace

### 3.7.5 Tangible test results X6 (selection)

In Figure 06 to Figure 11 a selection of X6- representation results are shown. The presented selection has no particular order or based on qualitative indicators. The images show the variety and diversity in solutions and representational visualizations.

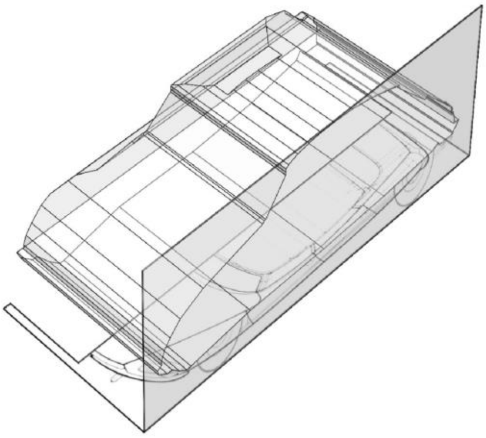


**Fig. X6-04** 3-D CAD sketch participant no. X6-19

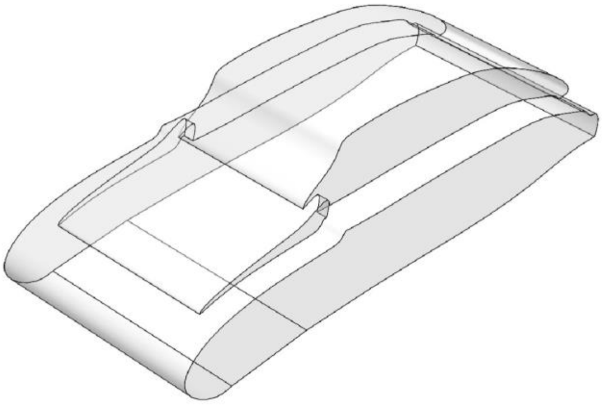


**Fig. X6-05** 3-D CAD sketch participant no. X6-20

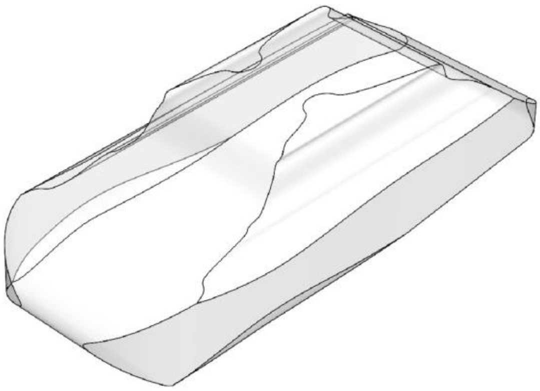


**Fig. X6-06** 3-D CAD sketch participant no. X6-12

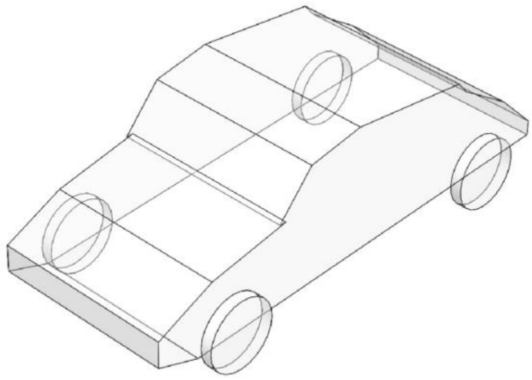


**Fig. X6-07** 3-D CAD sketch participant no. X6-01

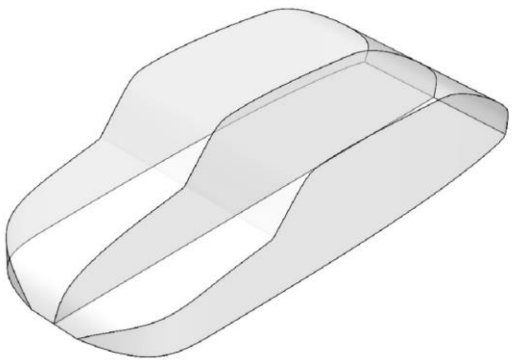


**Fig. X6-08** 3-D CAD sketch participant no. X6-22

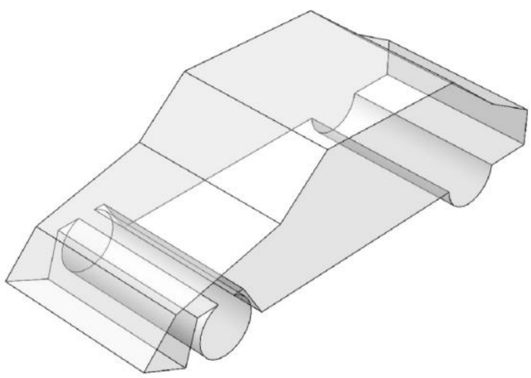


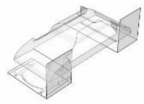
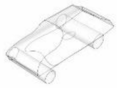
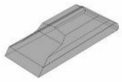
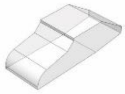
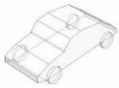
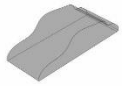
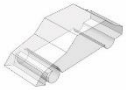
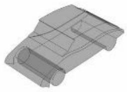
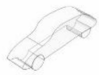
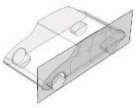
**Fig. X6-09** 3-D CAD sketch participant no. X6-18

For more results of other participants see Table X6-2.

### 3.7.6 Overall ranking results 3-D Solid Works test

**Table X6-2** Time & quality combined (left to right - top to bottom)

Left to Right - Top to Bottom (22 results)

| | | | | |
|---|---|---|---|---|
|  **X6-03** Illanit |  **X6-19** Leon |  **X6-11** Robin |  **X6-20** Jeroen |  **X6-04** Christiaan |
|  **X6-10** Wilco |  **X6-21** Wout |  **X6-12** Joris |  **X6-14** Tineke |  **X6-07** Mike |
|  **X6-02** Sefrijn |  **X6-01** Eilien |  **X6-15** Paul |  **X6-22** Hugo |  **X6-09** Sophie |
|  **X6-06** David |  **X6-18** Jennifer |  **X6-16** Frank |  **X6-13** Hedde |  **X6-17** Rachel |
|  **X6-05** Anton |  **X6-08** Nienke | | | |

### 3.7.7 Analysis and evaluation X6

In figure X6-12 individual iteration and processing time of the 22 participants in X6 are shown.

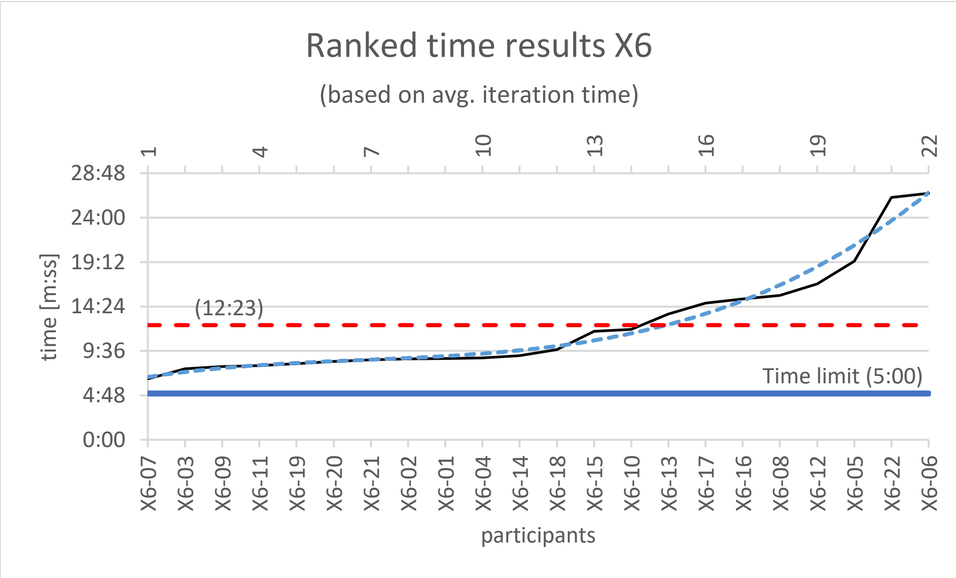



**Fig. X6-10** Ranked by time (left = fast, right = slow)

Presented in Fig. X6-10 are all 22 individual results (black jagged line). A steady upward curve (3rd order polynomial) trend line (blue dashed line) results in a CC = 98,6 %. The average iteration time is 12’ 23” (red dash line) which exceeds the 5 minutes time limit.

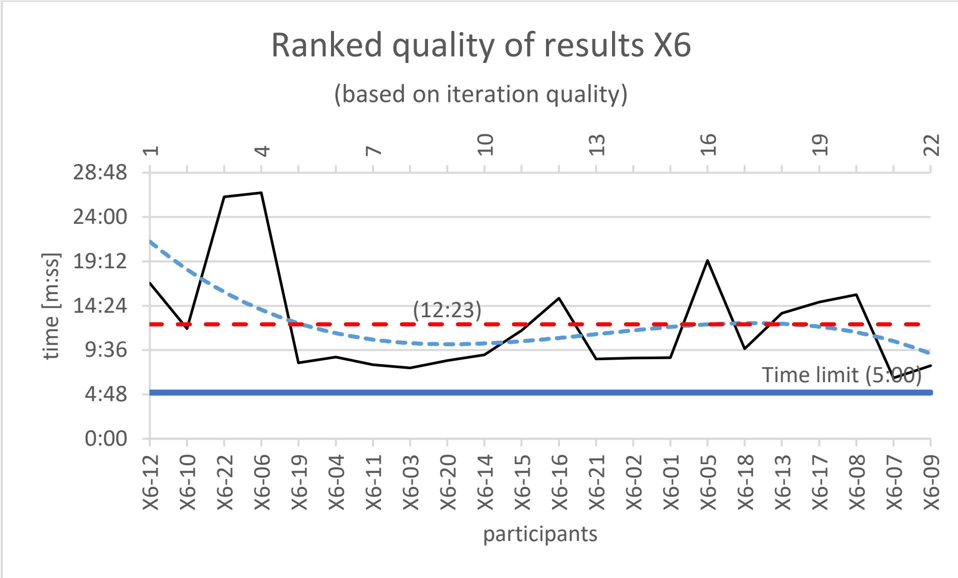



**Fig. X6-11** Ranked by quality (left = good, right = sufficient)

When we display the quality ranked iterations as in Fig. X6-11, the data points get more irregular and jagged (black line). The (3rd order polynomial) trend line (blue dashed line) becomes an undulated curved and sloped with a CC = 49,6 %.

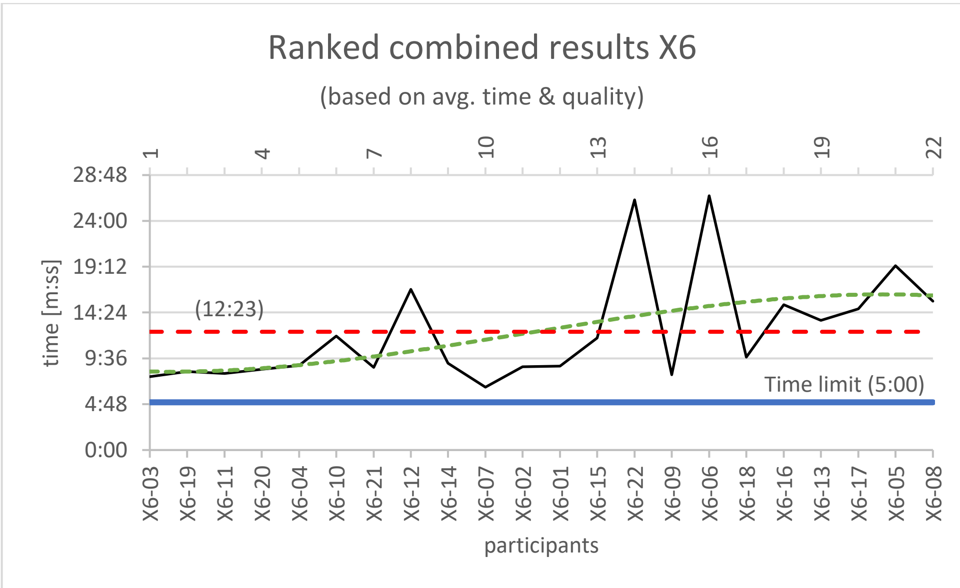



**Fig. X6-12** Ranked by combined results (left = good, right = sufficient)

In Fig. X6-12 we present the individual quality ranked iterations (black jagged line). The data points get more smoothed out and the (3rd order polynomial) trend line X6 (green undulated dash line) becomes more straight with a CC = 53,7 %.

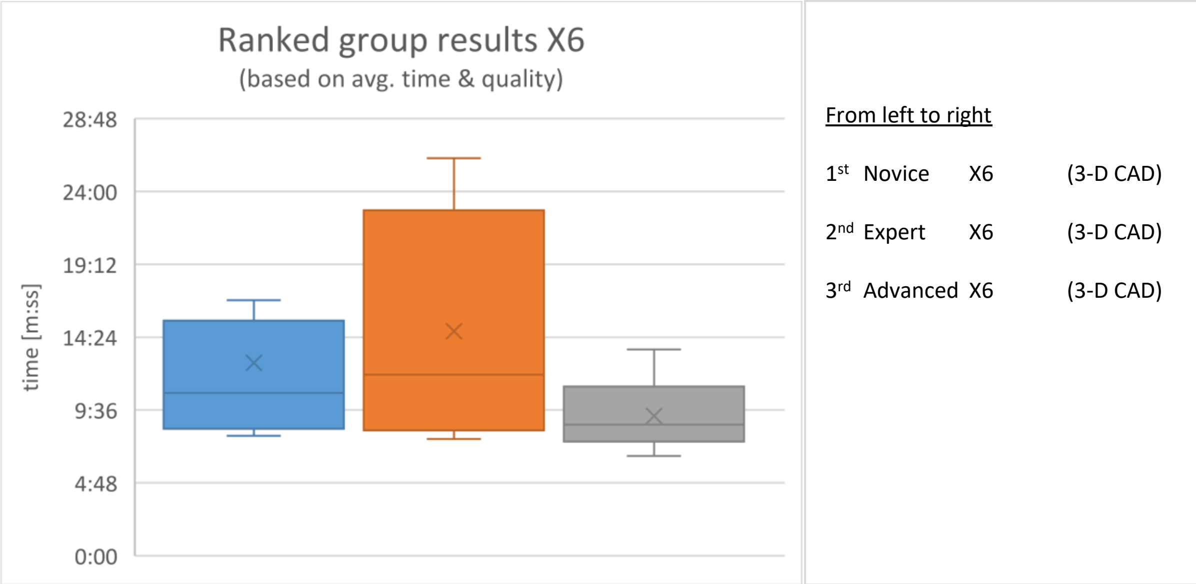



**Fig. X6-13** Ranked by expertise group (left = high-end, right = low-end)

In Figure X6-13 we show the specific results per expertise group. In X6 the Novice group shows more skills and speed, compared to the Experts and Advanced groups. See Table 6-3 in Appendix A on how the group ranking is achieved. The ranking is based on the iteration time (speed), tacit-tangible skills, and quality of the executed design task. The best individual result was from an expert, while the novice group performed best in total for this X6 test.

## 3.8 Experiment 7 – (3-D) Virtual Clay with Haptic Force-Feedback Device

Experiment 7 (X7) is based on 3-D virtual sculpting in conjunction with Sensable® ClayTools™ (CT) v. 2.0 (virtual clay modelling software) and a 6-DOF Sensable® Phantom Omni touch-haptic device (see Figure X7-01).[7] A group of 21 individual participants (14 male and 7 female) executed this seventh test. This X7 group consisted of 57 % BSc. (novice) and 29 % MSc. students (advanced) in the age of 18-52 years. The final 14 % were expert designers (i.e. lecturers IDE) in the age of 23-36 years. A detailed overview of participants is shown in Table X7-1.

**Table X7-1** Overview participants Experiment 7

| | | | | | | |
|---|---|---|---|---|---|---|
| **Participants X7** (3-D Virtual Clay) | 21 | 14 | 7 | 12 | 6 | 3 |
| | 100 % | 67 % | 33 % | 57 % | 29 % | 14 % |
| | 18-52 years | | | 18-52 years | | 23-36 years |
| | **Total** | **Male** | **Female** | **Novice** | **Advanced** | **Expert** |

### 3.8.1 Typical setup X7

The X7-setup is kept very simple and effective in lay-out. A chair and a table allow the participant to comfortably sit and work during the test. In X7 a generic Windows laptop (OS-Win XP) configured with the CT-application was facilitated. A five-minute time limit is set for this experiment. However, in some cases we allowed additional time (Fig. X7-02).

[7] https://vimeo.com/10351524

### 3.8.2 Design representation task description X7

The participant is seated during the duration and execution of the test. The facilitator's role is to instruct, observe, and capture the user-interaction (UIA) on video (Fig. X7-01). The facilitator provides a brief set of instructions and explains the X7 procedure as follows;

- We facilitated a 3-D virtual clay-mass with projected elevation of the orthogonal drawing of the Citroën DS (see Figure X7-03) in the CT workspace
- In addition, the 2-D A4 orthogonal projection was provided
- The design task and procedure of X7 is explained to the user
- The facilitator asks consent of the user to capture UIA on video
- A time constraint of 5 minutes is instructed. However, this seemed highly unrealistic right from the start. We allowed 10-15 minutes extra in order to gain 'tangible' results
- Start and execution of design task X7

**Fig. X7-01** Setup virtual clay haptic bench (X7)

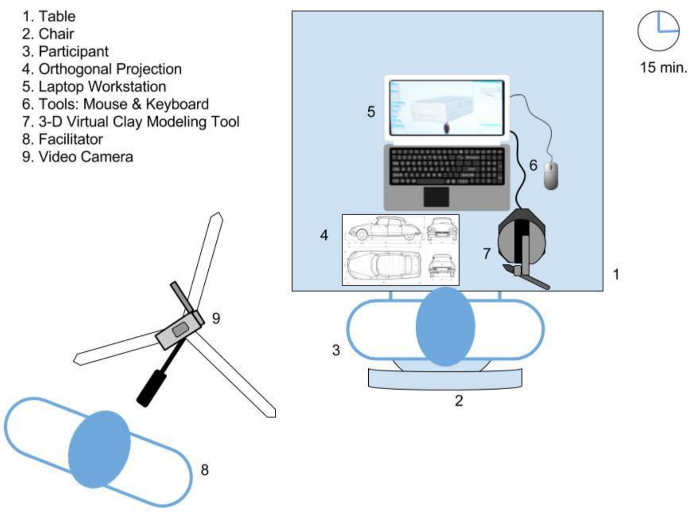



**Fig. X7-02** Diagram of setup X7

### 3.8.3 Representation task X7

Individual participants are asked to interpret and create 3-D virtual clay-models based on the representation of the artefact in the 3-D size constraint bounding box (Fig. X7-03). To lower the threshold in learning we provided this three-dimensional workspace including views and elevations of the artefact. In addition, the 2-D orthogonal drawing of the artefact is supplied as source of reference (Fig. X7-02 No. 4). The goal is to 3-D sketch/sculpt, represent, and interpret as fast as possible the main features and characteristics of the automotive artefact. This constraint-based procedure is necessary to be able to compare (rank) the individual sketches, effectiveness and quality of the results after the experimentation concluded.

### 3.8.4 User interaction X7

The designer has to have a good mental image, detailed insight and understanding of the total 'volumetric' shape before commencing with the modelling. (Fig. X7-03) Since all the views and elevations merge into one or several fluent and curving lines the shape and form should be clear in advance.

We provided a block shape of virtual clay including views and elevations of the artefact to lower the learning threshold and to allow the participant to concentrate directly on the task. Again, we had to allow for more time because of difficulties with the virtual clay application and the haptic device. Most participants experienced the high learning threshold and curve of both the tool and the application. This had a major influence on their actions, interactions, iterations, and on their sensory perception. For some these problems became so frustrating that they quit or gave-up the design task before they "even got started."

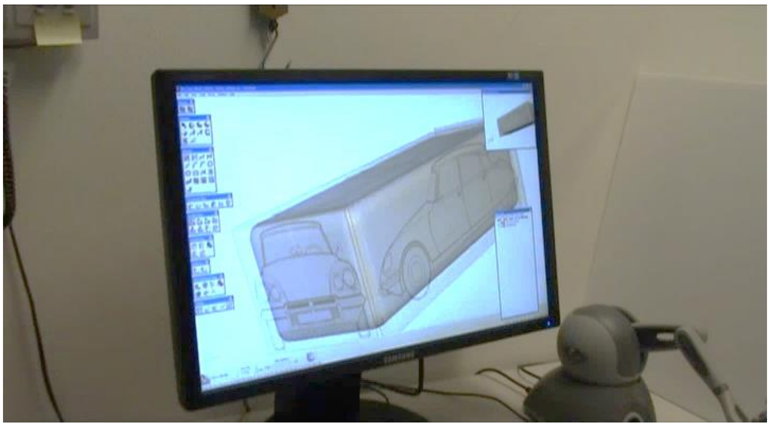


**Fig. X7-03** Start of test procedure participant with modelling constraint

### 3.8.5 Tangible test results X7 (selection)

In Figure X7-06 to Figure X7-11 a selection of X7- representation results are shown. The presented selection has no particular order or based on qualitative indicators. The images show the variety and diversity in solutions and representational visualizations.

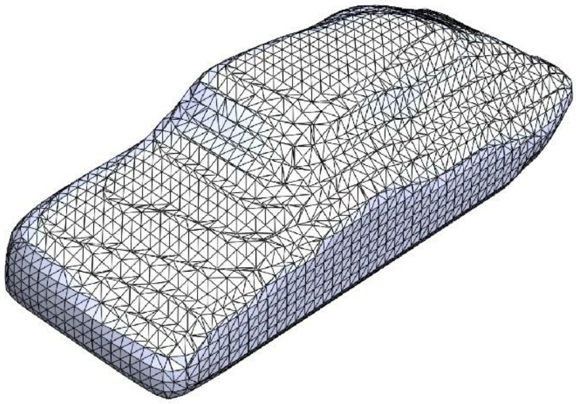


**Fig. X7-04** 3-D virtual clay-model participant no. X7-09

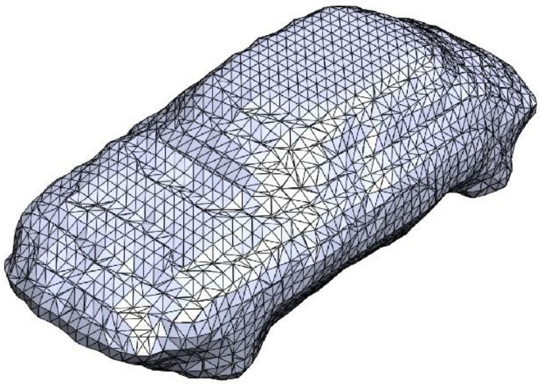


**Fig. X7-05** 3-D virtual clay-model participant no. X7-04

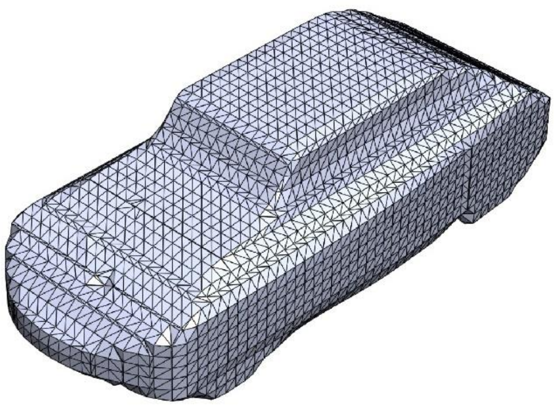


**Fig. X7-06** 3-D virtual clay-model participant no. X7-17

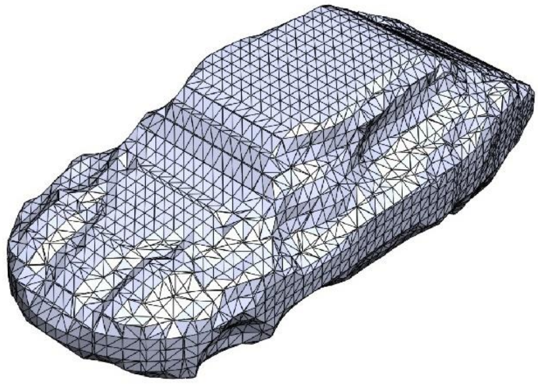


**Fig. X7-07** 3-D virtual clay-model participant no. X7-21

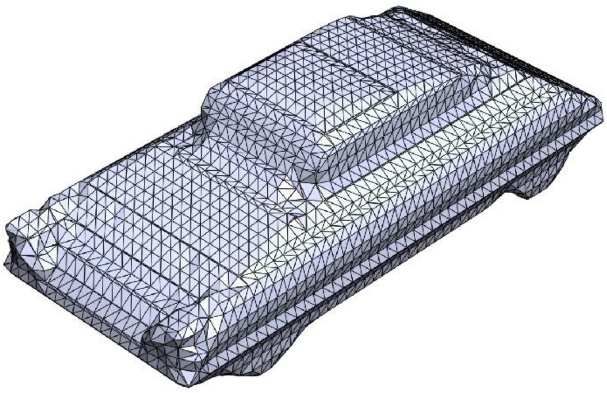


**Fig. X7-08** 3-D virtual clay-model participant no. X7-13

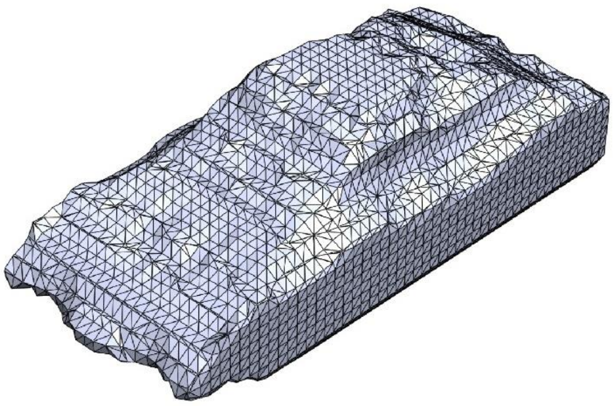


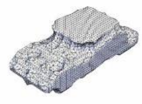
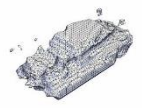
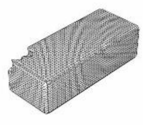
**Fig. X7-09** 3-D virtual clay-model participant no. X7-15

For more results of other participants see Table X7-2.

### 3.8.6 Overall ranking results virtual clay test

**Table X7-2** Time & quality combined (left to right - top to bottom)

Left to Right - Top to Bottom (21 results)

| | | | | |
|---|---|---|---|---|
|  **X7-09** Jennifer |  **X7-19** Dennis |  **X7-01** Mike |  **X7-04** Joris |  **X7-08** Frank |
|  **X7-05** Sophie |  **X7-11** Wouter |  **X7-10** Leon |  **X7-17** Sander |  **X7-16** Gerben |
|  **X7-07** Paul |  **X7-21** Christiaan |  **X7-13** Sefrijn |  **X7-03** Robin |  **X7-14** Wout |
|  **X7-18** Marijn |  **X7-06** Tineke |  **X7-12** Jeroen |  **X7-15** Hugo |  **X7-20** Puck |
|  **X7-02** Wilco | | | | |

### 3.8.7 Analysis and evaluation X7

In figure X7-12 individual iteration and processing time of the 21 participants in X7 are presented.

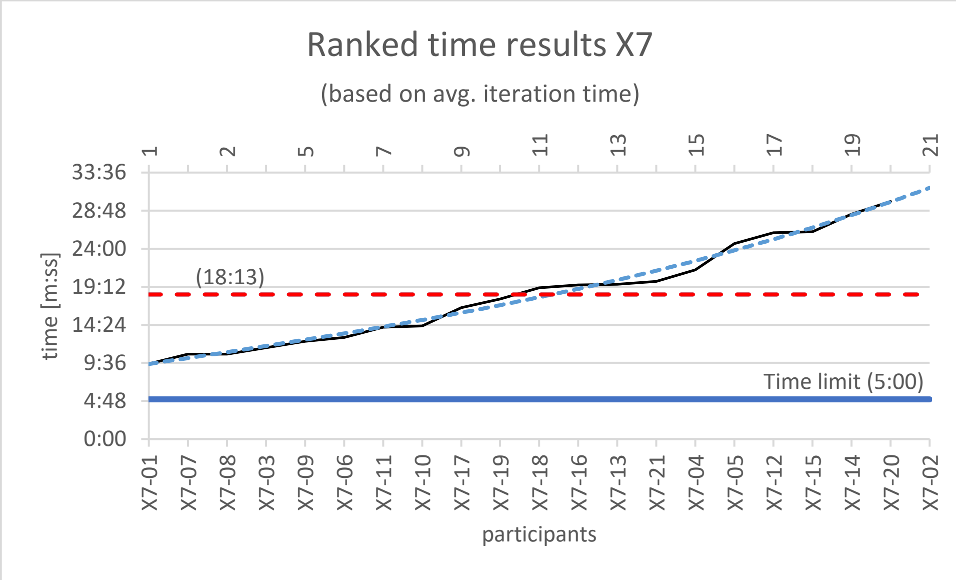



**Fig. X7-10** Ranked by time (left = fast, right = slow)

Presented in Fig. X7-10 are all 22 individual results (black jagged line). A steady upward curve (3rd order polynomial) trend line (blue dashed line) results in a CC = 99,4 %. The average iteration time is 18’ 13” (red dash line) which exceeds the 5 minutes time limit.

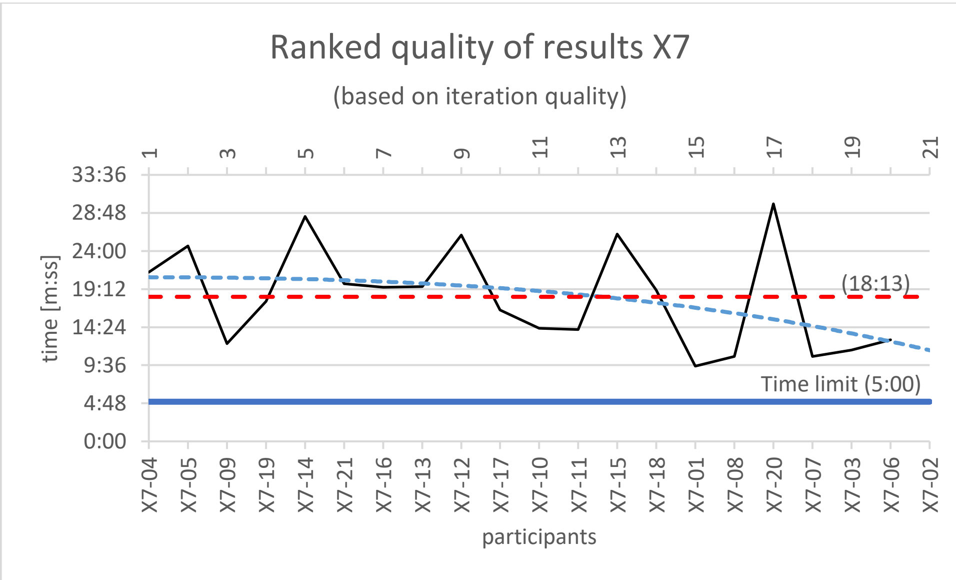



**Fig. X7-11** Ranked by quality (left = good, right = sufficient)

When we display the quality ranked iterations as in Fig. X7-11, the data points get more irregular and jagged (black line). The (3rd order polynomial) trend line (blue dashed line) becomes convex curved and sloped with a CC = 40,7 %.

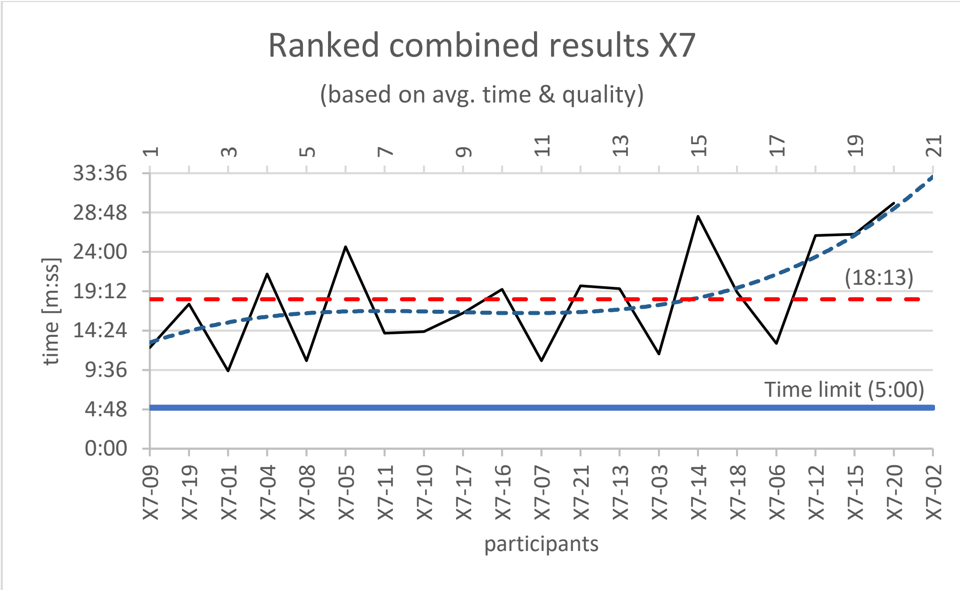



**Fig. X7-12** Ranked by combined results (left = good, right = sufficient)

In Fig. X7-12 we present the individual quality ranked iterations (black jagged line). The data points get more smoothed out and the (3rd order polynomial) trend line X7 (dark blue undulated dash line) becomes more straight with a CC = 62,9 %.

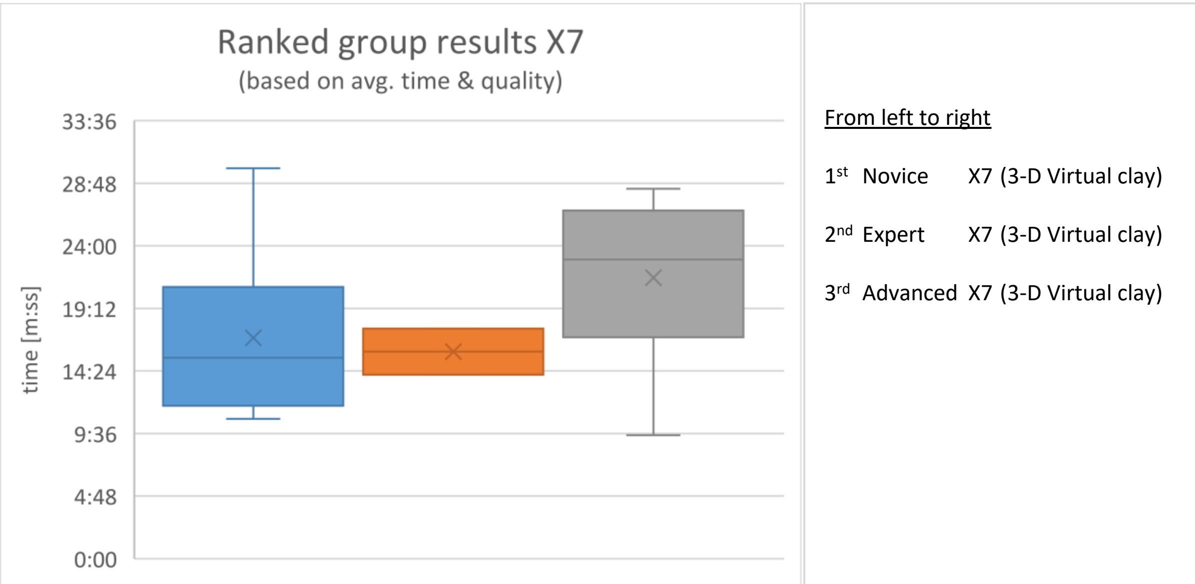



**Fig. X7-13** Ranked by expertise group (left = high-end, right = low-end)

In Figure X7-13 we show the specific results per expertise group. In X7 the Novice group shows more skills and speed, compared to the Experts and Advanced groups. See Table 7-3 in Appendix A on how the group ranking is achieved. The ranking is based on the iteration time (speed), tacit-tangible skills, and quality of the executed design task. The best individual result was from a novice and the same novice group performed best in total for this X7 test.

## 3.9 Analysis method and results

Video Interaction Analysis (VIA) (Jordan & Henderson, 1995) was used to investigate the gestures, expressions, actions, immediacy (context), iterations and interactions with hardware and software.

Video recording enables us to make qualitative evaluations of the various tests. Data was extracted from the video footage from the various test benches. We assessed 208 participant tests by students and experts. Twenty-seven hours of video captured interaction during a 3 months period, which resulted in a great amount of data. All the participants were made aware of the video recording, but no further reference was made to the video camera during the assessments. A quantitative selection of 83 participants was targeted and provisional conclusions were drawn from the selected and collected raw data. The on-the-fly ideation of a design task and representing it either abstractly or tangibly showed us that a haptic interface is very useful (Wendrich, 2010). Results show us that tangible interaction has merit, speeds up interaction, lowers threshold in learning curve and stimulates flow and engagement. Untethered two-handed interaction is adding more quality, more detail, and it conveys higher end-output. Less demanding interfaces steam up the pace and create flow in interaction. The force feedback from physical materials enhances concentration and involvement in the design task. The use of digital devices (i.e. mouse, keyboard) and the use of a force-feedback device in ideation and conceptualization did not prove to be very effective. In some cases the participants gave up or became frustrated with their results showing on the screen. We observed the same duality in the results and representations as we did with the tangible experiments in an educational context. Every method has its own specific interaction, use of physical manipulation, tacit knowing and idiosyncratic progression (Wendrich, 2010). By setting tight time limits, we were able to speed up choice-architecture and decision-making during processing, which resulting in a larger variety of qualitative results. In our preliminary analysis and evaluation of the results, we concluded that even though the given task was the same for all participants, they all executed their ideas and notions based on their individual skills, insight, understanding and tacit knowing. From these preliminary findings we constructed a conceptual framework for interaction design (IxD) that incorporates tacit tangible interaction. With this we plan to explore the possibilities of creating an intuitive product design tool. The following section show the combined results of the seven test benches (Wendrich, 2010).

### 3.9.1 Combined results normalised over seven experiments

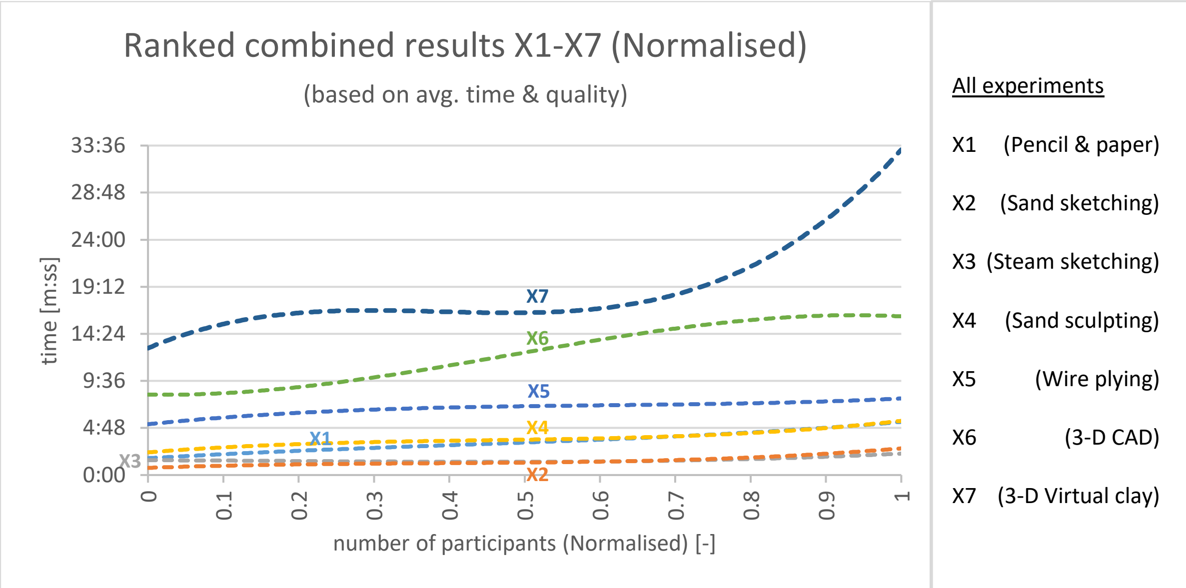



**Fig. 3-1** Ranked by combined results (left = good, right = poor)

Relational aspects and issues are covered completely. Everything is related and connected per experiment but also combined based on all aspects of the overall experiments. The end results of findings and experimental data give an answer (*possible solution) to the research question(-s). Figure 3-1 shows the correlations between skill sets (i.e. novice, advanced, expert), time constraints, performance, familiarity, tool affordances, and effectiveness of tool interaction. Representational qualities are defined and established on basis of mean quality (MQ) (see Chapter 2.4 – 2.7). MQ means: role-model based on Flaminio Bertoni's 2-D and 3-D models (Fig. 2-7) and real-world automotive design icon (Fig. 2-1). We performed a comparison based on the MQ and assessed the externalized 2-D and 3-D representations as tested in these experiments. Qualitative rankings are based on MQ + qualitative ranking based on tool interaction, performance, quality and iteration speed.

The diagram shown in Fig. 3-1, is the aggregate of all seven experiments combined. The correlation between the individual experiments are clearly visible. Every tool, even though the tool is used for the same design-task, has its own effectiveness, quality, constraint, threshold, and interaction modality. So, question here is, how much aided is there in computer-assisted drawing/modelling (CAD)? Therefore, we propose human-aided design (HAD) in conjunction with computational systems and affordances. In Chapter 4 a novel approach and concept proposal of such a HDT-system will be further elaborated and explained.

The final step is normalisation of the number of participants over all seven experiments that includes overall ranking results combined ([T+Q] /2) and normalised ([Rank -1]/Rank max). Presented are the resulting seven trend lines X1 through X7 for comparison, evaluation and visualization of the individual characteristics and aspects of the seven representational experiments. Clearly visible is how the analogue (X1 to X5) and digital (X6 & X7) experiments outcomes differ and significantly show an increase in time, performance and qualitative issues.

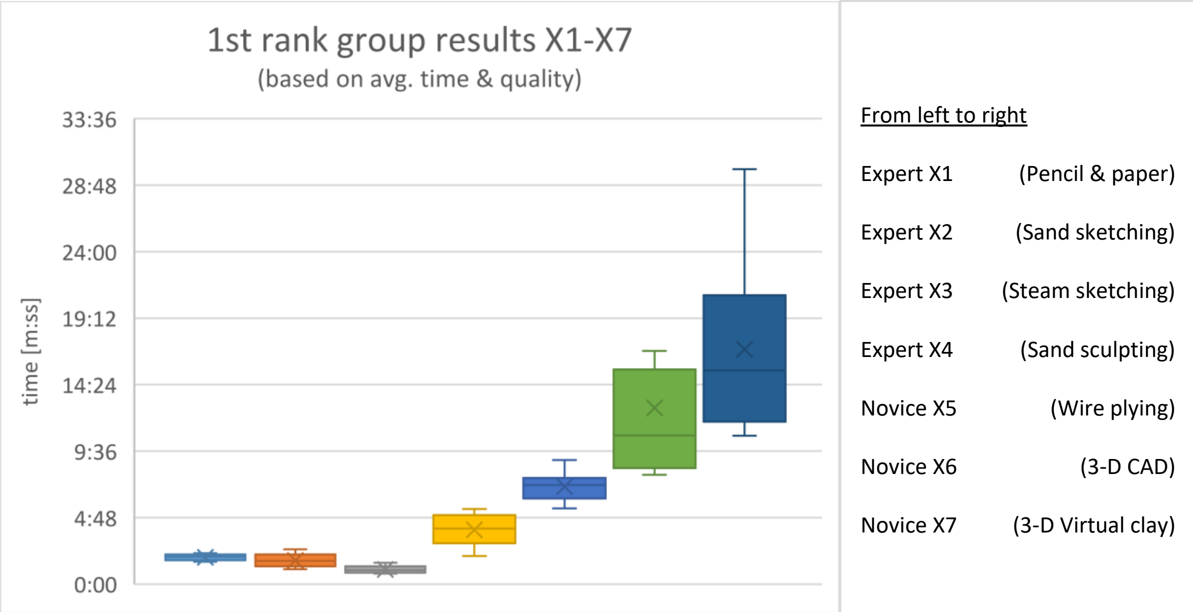



**Fig. 3-2** Best group per experiment (1st rank)

In Fig. 3-2 for X1 to X4 the expert participants lead the test results and for X5 to X7 the novice participants perform better. See also Appendix B for more details on the group ranking.

As expected the first five (analogue) experiments are based on traditional design tools. They are low tech, low level in tool/material constraints and demand a high degree of tactile (manual) interaction. The final two experiments are fully digital in setup and execution. The apparent constraints raised by digital CAD platforms, due to program-directions, interface constraints (both on screen and at hand) often forces the participants to make trade-offs and misinterpretations. This leads to gradually loss of interest or frustration with the procedural progression or acquired end result. Some participants however, got competitive and tried to improve the result by detailing and reiterating the outcome. This way the iteration time started to climb dramatically and the experiment was interrupted by the facilitator. All intermediate and final results obtained from the participants were sufficient to process as data for this master assignment.

# CHAPTER 4 - EARLY PHASE PROTOTYPING RSFF TOOLS

## 4.1 Towards tacit tangible CAD systems

We set out to combine all our gathered data, research findings, results, and explorations to devise a system that hands-back control to the designer, without substituting or replacing the computer! We now consider the computer as an assistant to support our tinkering, modelling, and design processing. We use our conceptual interaction framework (Fig. 4-1), including data from our technology scan (Wendrich & Tideman, 2004) for the analysis and evaluation of tangible interactions as a function of multiple dimensions (XD), trying to create insight and understanding of the different levels of abstractions, and the similarities and differences between the physical and digital modelling activities.

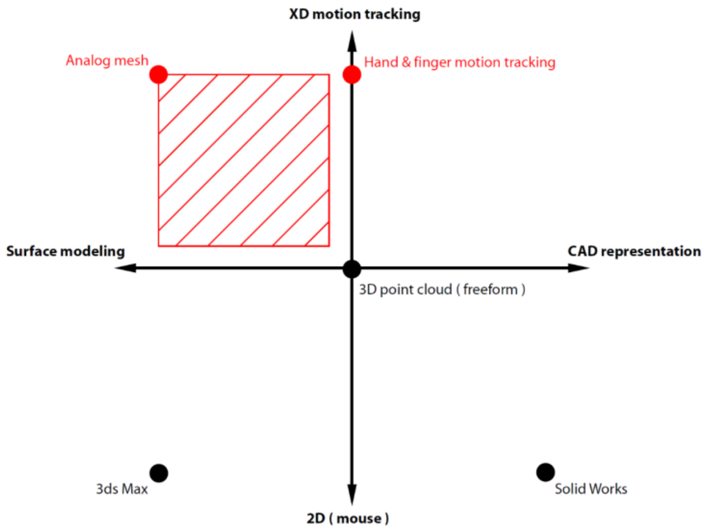



**Fig. 4-1** Research framework comparing various CAD design interaction tools

The framework enables us to explore various aspects in the user interaction domain, user intuition, device and tool functionalities. It also allows us to investigate emerging program directions for future CAD systems. The preliminary results and datasets from our experimentation procedures show that, with respect to ideation and conceptualization, tacit and tangible iterations are easier, more direct, faster and more intuitive than commonly available digital tools or software methods. During ideation or creation of concept the ability to create, to imagine and to associate freely with abstract or tangible materials are considered crucial factors for an effective design process. Bringing back tangible interactions, and allowing tacit knowing and designer skills to emerge, will lead to more creative output in a shorter time span.

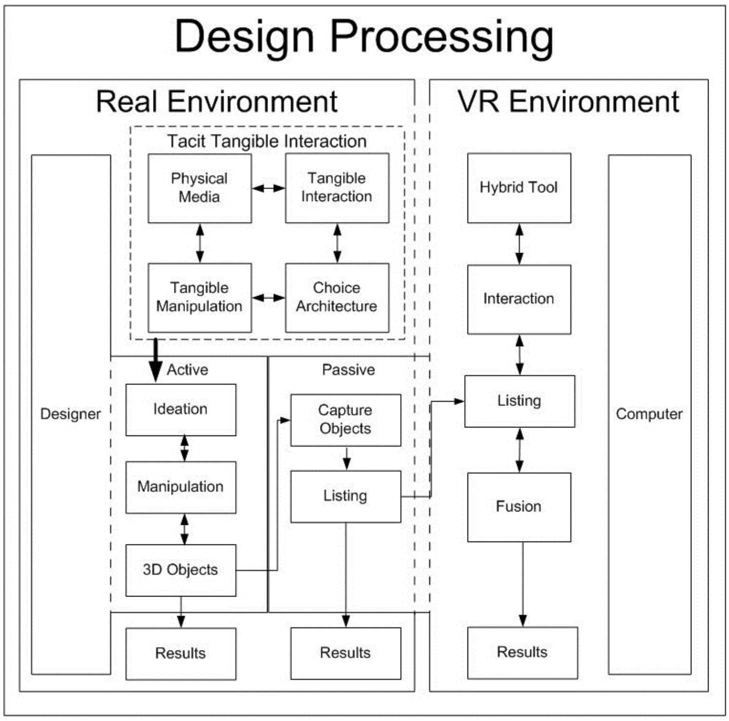



**Fig. 4-2** Design processing using physical and digital representation as envisioned in Rawshaping Formfinding (RSFF © 2008)

The virtual design assistant (VDA) named RSFF-HDT (Fig. 4-2) stores the captured iterations as polygon meshes (listing) by mimicking the tangible representations, and storing them in a database as time-stamped snapshots. By creating such a timeline of the evolving tangible object manipulations captured by means of a vision system, the hybrid tool allows the fusion of different polygon meshes with subsequent optimization. The RSFF design tool and process chart indicates how the active and passive interactions are embedded in the hybrid design tool (HDT) (Fig. 4-3). We believe that such a tool will be a valuable addition to the panoply of current design tools and methods.

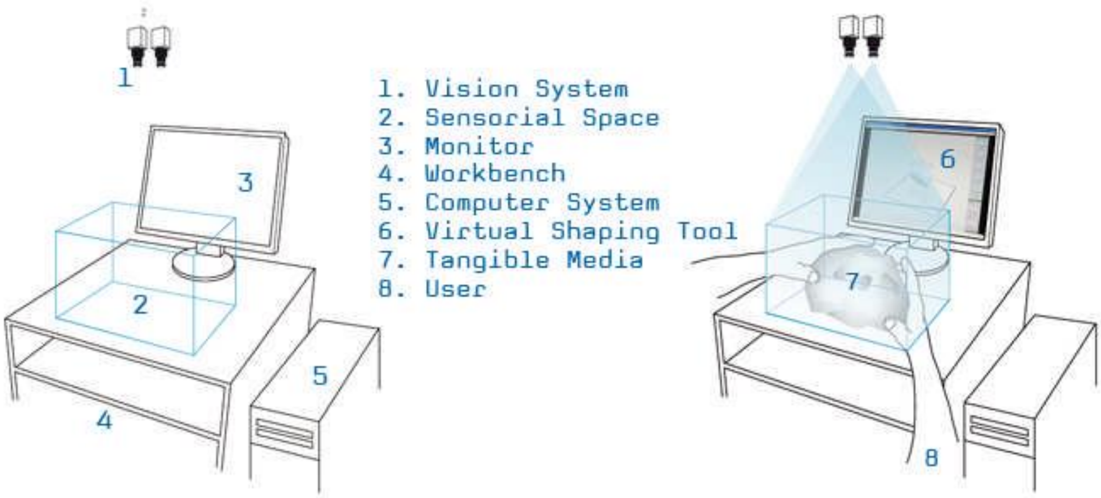



**Fig. 4-3** Setup VDA workbench and RSFF-HDT

## 4.2 Design and Build a Functional RSFF-HDT Prototype

We started with mapping and studying the feasibility of developing and building a functional prototype of the envisioned RSFF-HDT (Fig. 4-4 and Fig. 4-8). Our main goal is to create fully-functional prototypes based on the low-cost, high value principle in corporation with commercial-off-the-shelf (COTS) components. The first tool, that was created in 2009 by the RST research group, used a stereo-vision camera system for high-speed tracking of objects or artefacts. The virtual simulations were generated real-time and visualized as polygon-mesh representations on screen. The computational-vision system made a predetermined timed snapshot of the bimanual iterative manipulations that were generated by the user (sensorial space) with tangible materials and artefacts (See Fig. 4-3, Fig. 4-6, Fig. 4-7). Further exploration and investigation lead to a plethora in vision-system candidates and possible solutions for the basic HDT-system technologies.

### 4.2.1 Vision system and 3-D image acquisition

A good candidate for real-time 3-D image acquisition is dense stereo depth mapping; this is probably the only feasible approach with low-cost hardware. The simplest setup requires two cameras to be roughly parallel to one another. Image acquisition should occur as close as possible to simultaneously near real-time from both cameras, which could prove to be slightly problematic when for instance making use of USB webcams (Fig. 4-5). The main advantage of using USB webcams is the low-cost aspect. Disadvantages include grainy images, bad drivers with built-in gamma correction, relatively low framerate and the USB bus that usually does not provide enough bandwidth to handle two cameras at the same time (i.e. no high value). Using webcams also means that the acquisition setup is very sensitive to lighting conditions. Ideally, one would use a camera with a (infrared) lens filter, a relatively long shutter time and some kind of (infrared) flashing system. Again, this would need to be synchronized with the rest of image acquisition. The USB bus issue can be avoided by either making use of webcams that have efficient drivers that don't need more than around 40 % of the total available bandwidth, or separate USB controllers per camera. Another option is to make use of FireWire or gigabit cameras, although these are generally a lot more expensive.

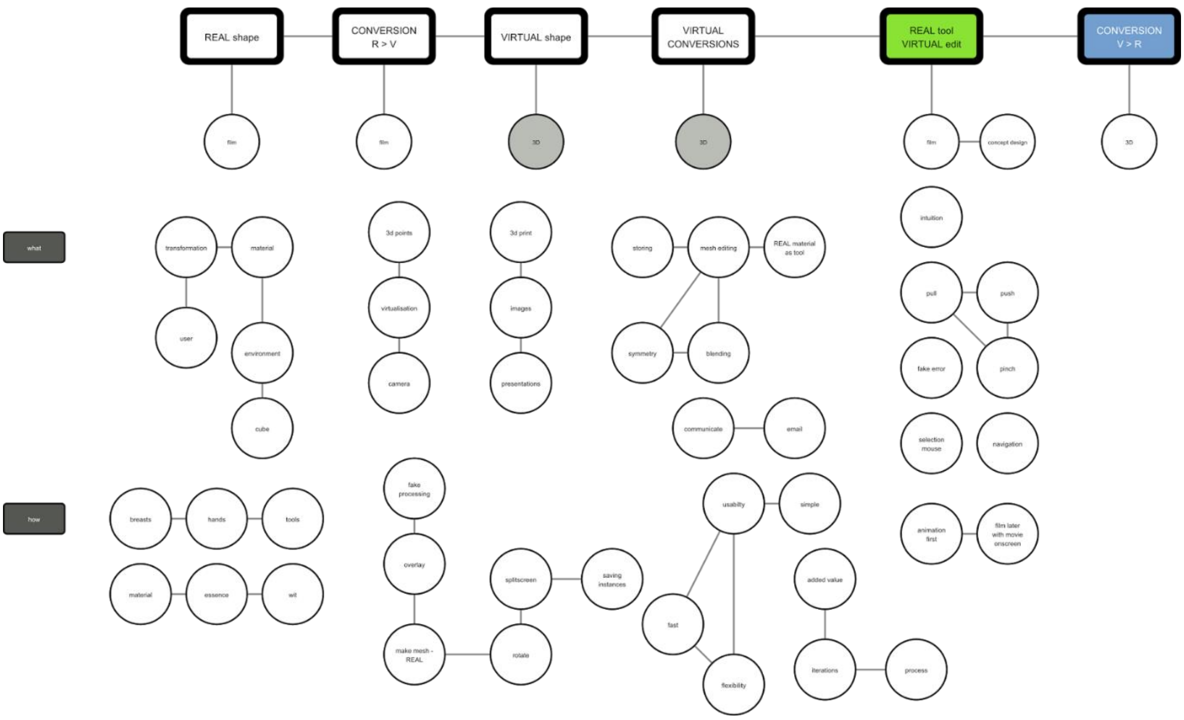



**Fig. 4-4** Prototype RSFF-HDT Feasibility Scan

**Fig. 4-5** Prototype early phase RSFF-HDT, including hi-speed cameras and USB webcams

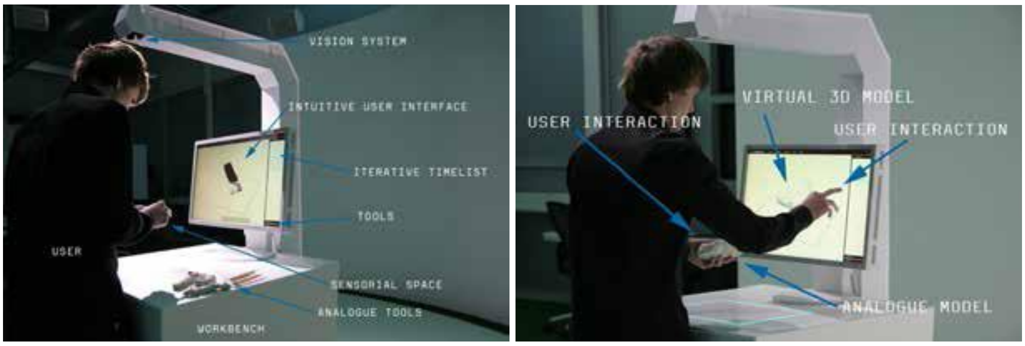



**Fig. 4-6** User interaction and hybrid design tool system equipped with stereo cameras

In the typical RSFF-HDT setup basic prototype concept a monitor acts as a proscenium to a virtual reality (McCullough, 1996). The user interaction takes place in a metaphorical 'sensorial space', in which manipulation and transformation of malleable material and/or other plausible materials take place (Fig. 4-3, Fig. 4-6, Fig. 4-7, Fig. 4-10, Fig. 4-11). The user can decide at any moment during or after processing to reiterate or reconfigure the iterative content by blending and morphing the individual virtual instances to create new virtual models or objects. Optimization and redistribution of forms and reshaping parts or whole bodies is afforded by the multi-touch surface. The user interaction is either based on intuitive notions starting from scratch and shaping tangible materials to externalize a low-fidelity model or e.g. Voronoi structure (tessellation) to visualize a conceptual idea or construct. The system represents a real-time interpretation of the rough modelled shape, e.g. a wireframe or surface-model, in many cases a low-fidelity model is more important than an accurate model (Fig. 4-11, Fig. 4-12).

**Fig. 4-7** Tacit-tangible modelling, virtual modelling,3-D AM modelling, interface visualization and iterative process steps with RSFF tool.

### 4.2.2 Tacit- tangible CAD interaction with RSFF-HDT

The RSFF-HDT[8] is conceived to also interact with the subsequent phases in design and engineering of for example an actual product. There is a possibility to insert raw functional elements (i.e. mechanical parts or printed circuit boards) as part of the assembly in the mesh iterations, or to fit the emerging shape to the functional and technical requirements with the use of appropriate simulators. The generated meshes can also readily be exported to produce tangible models with e.g. additive manufacturing (AM) (Fig. 4-7). We designed and created a prototype of a two-handed physical representation workbench with stereo-vision based components (i.e. hi-speed cameras) that capture the iterations during design processing (Fig. 4-8, Fig. 4-9).

**Fig. 4-8** Setup workbench virtual embodiment and physical prototype RSFF-HDT

The designer standing at the workbench is tinkering, thinking, and designing physically, processing ideas with tangible materials to shape and form possible solutions (Fig. 4-6, Fig. 4-7, Fig. 4-9 and

[8] https://vimeo.com/43850666

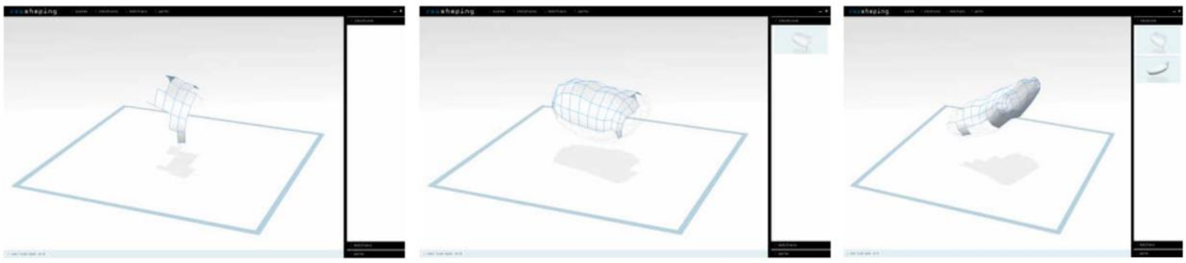
Fig. 4-10). It is also possible to reverse-engineer, retro-fit, and/or re-design starting from an existing product or 3-D object.

**Fig. 4-9** The designer engaged in physical interaction standing at workbench

There is no need to look at the monitor during the initial physical interaction and execution phases of the design task. The designer is untethered and can freely manipulate materials, create various physical models, and concentrate on the work. The rawshaping-methodology creates room for re-shaping, styling, form giving, and applying geometrical corrections in combination with e.g. other CAD tools, while at the same time leaving for example, the idiosyncratic mark (signature) of the designer intact.

**Fig. 4-10** Interaction with the RSFF- HDT

Various stages of the design evolution are captured as raw polygon meshes (Fig. 4-11). They are also stored in a database that is shown as a listing (history) and is also directly visible on the monitor in a separate solution space window (Fig. 4-11 a - i, and Fig. 4-7 top-right).



a b c

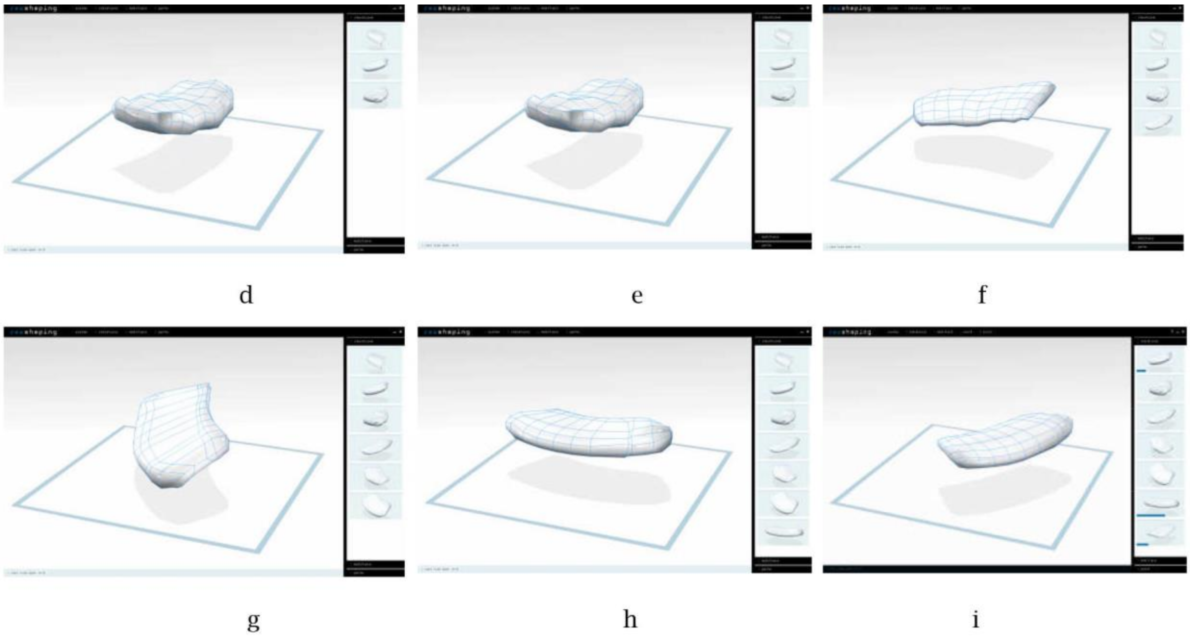



**Fig. 4-11** Sequences of iterative meshes during an evolving design process (a-i) on the RSFF-HDT

When the designer decides that sufficient tangible results have been generated and the outcome of the design processing is deemed satisfactory, the HDT will be used in a new mode. The stored shapes (polygon-meshes) are reviewed and ranked as to which of them fit the requirements (Fig. 4-12). They can then be combined, morphed, and used to synthesize novel and more refined solutions (Fig. 4-7, Fig. 4-12 right).

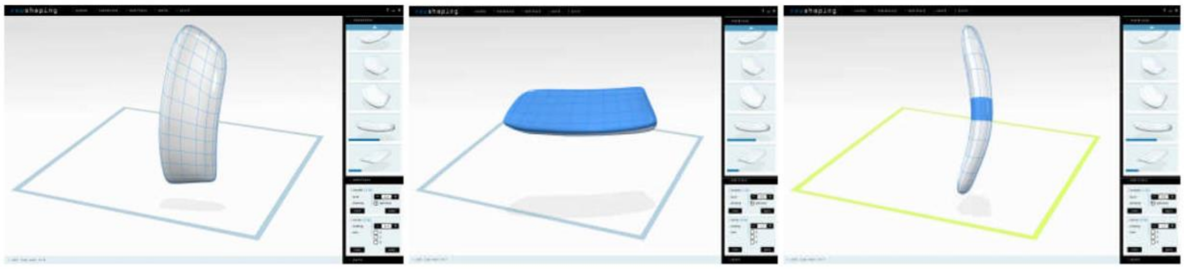


**Fig. 4-12** Virtual shaping tool in action – polygon mesh iterations and transformations

Again, the designer is in control of this selection, sorting, choice-architecture and decision-making process. To enable this interaction, the system incorporates a multi-touch screen to support the designer during this step in the process (Fig. 4-10 right). This suggested feeling of real-touch stems from virtually touching on screen 'your shape' or 'product form' and augments the real with the virtual environment. It reconnects the designer with the virtual artefact and reinforces the feeling of engagement. Besides, it could stimulate enjoyment to work, engage and immerse oneself within synthesized design environments. To hand the designer the feeling of control over his virtual shape by means of on-screen bimanual interaction, the engagement with the virtual artefact becomes hyper-mediated. Hyper-mediation suggests in this context, not so much "being fully immersed", however as "being interrelated or feeling connected" (ibid. Bolter & Grusin, 2000).

## 4.3 Next Step RSFF-HDT Prototype with Kinect and Principle Functionality

This next RSFF-HDT prototype has been developed using common off the shelf hardware - a normal desktop computer (3.2 Ghz quad-core with a Nvidia 9600GT video card) running Microsoft Windows

7 and a Microsoft Kinect is being used to capture both visual and 3-D information, acting as video camera and depth measurement device (Fig. 4-13 and Fig. 4-14).

**Fig. 4-13** Prototype Early Phase RSFF Tool with Kinect (left), Virtual Instances and Visualization

The software makes use of various open-source libraries; the GUI system is implemented with Qt [qt], the 3-D view is based on OpenSceneGraph [osg], and OpenNI [oni] is used to acquire the data generated by the Kinect. These subsystems are integrated in a custom framework that allows for library encapsulation, parallel task execution and broadcast-style component communication (Dos Santos, Grevenstuk & Wendrich, 2009-2010).

When in live-viewing mode, the program continuously updates a 3-D model with newly acquired data from the Kinect. Several interpretations of the data can be made, and by default the model is updated with depth measurements only, without any specific kind of colouring. The data flow is illustrated in a schematic diagram (Fig. 4-14).

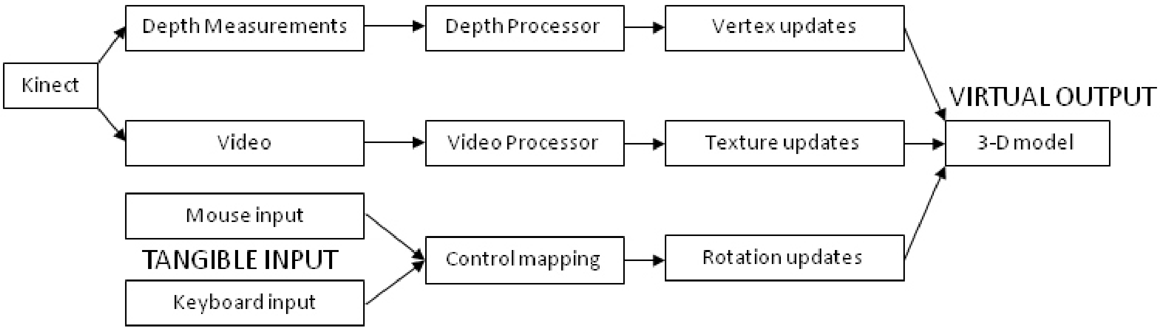



**Fig. 4-14** Data flow of RSFF tool system

The current setup allows for real-time capturing of 640x480 images with depth measurements for each pixel. The accuracy of the system varies depending on the distance to the depth sensor, no exact measurements are taken yet (Fig. 4-15). Some high-level issues and aspects needs to be addressed before a full functional prototype system could be made. The following issues are determined:

- image acquisition
- depth map construction
- converting depth maps into 3-D objects
- display and interaction with acquired 3-D objects
- multithreaded process management

**Fig. 4-15** Prototype early phase RSFF-HDT- equipped with Kinect and hybrid UIA and representation

For the proposed base software (open source) of the prototype system we refer to Appendix C.

### 4.3.1 Image acquisition with Kinect

The proposed depth map algorithm requires the input images to be calibrated, rectified [RECT] and undistorted. The calibration process should only have to be done once for each camera setup, as it estimates the relative position of each camera compared to one another. The calibration process will yield a single fundamental matrix [FUND] that can then be used to rectify images from this camera setup. Calibration is a sensitive process, and can yield varying results depending on the hardware in question and lighting conditions. The intended result of the image acquisition process is to acquire two undistorted and rectified images, preferably aligned along their epipolar lines [EPI] in order to greatly speed up the depth map construction process (Dos Santos, Grevenstuk & Wendrich, 2009-2010).

### 4.3.2 Depth map construction from Kinect data points

Dense stereo depth map construction has been an active subject of research, and is estimated that current commodity hardware should be fast enough to produce depth maps using this method at interactive rates. The depth algorithm in question (semi-global block matching) (Hirschmuller, 2008) is publicly available and implemented in the openCV image processing library, see Appendix C. The use of this algorithm will cut development time considerably. Roughly, the algorithm looks at n x n squares of pixels in one image and attempts to find similar blocks in the second image. When a match is found, the position where it was found is stored; assuming that the match is indeed the same area in the other image, there is an inverse proportional relation between the position where the match was found and the depth distance in 3-D to the camera. If no good match is found the area may be occluded in the other image; regardless, unreliable matches and/or mismatches should also be made available. An exact match is improbable, so the algorithm makes use of nearest hamming distance matches. Searching the entire image is an extremely lengthy process, and can be avoided by making use of epipolar alignment - when the cameras are positioned close to parallel to each other their images can be analysed to find horizontal equivalent lines, which restrict the search space of the stereo matching algorithm from the entire image to a single line of the other image. When imposing strict ordering on the matches, results should improve in quality, as the probability of bad matches goes down (Dos Santos, Grevenstuk & Wendrich, 2009-2010).
The algorithm can be tweaked with 11 variables, all of which are dependant of specific camera setups and image sizes, so finding an optimal set of parameters may take some effort as well. The matching process is straightforward but at the same time fairly brute-force and will take a considerable amount

of time to complete. There is an opportunity to perform the matching in parallel, suggesting possible speed improvements when the algorithm is implemented on the graphics processor. The graphics processor can be considered at a later stage to render the 3-D models as hardware optimization.

### 4.3.3 Converting depth map data into 3-D objects for 3-D modelling

The dense depth map needs to be converted into a 3-D object to be of any use in 3-D modelling. At the moment we feel that the process should be kept as simple as possible, keeping in mind that this stage needs to be reworked at a later point in time. The depth map shows a relationship between a pixel and its depth, and thus it should be fairly trivial to create a point grid with each point representing a pixel from the source image and then setting its depth by calculating it from the depth map. There is an issue with the amount of data processed however, as for even low input resolutions there are enormous amounts of data points to be calculated (640x480 -> 307200 points).

If this process proves to be a bottleneck, one can consider making the calculations in shader code on the graphics processor. Switching implementations from CPU to GPU code is not exactly trivial. For now we leave this apparent problem as a performance optimization opportunity and just try to get it to work first. In later versions, the model generation should attempt to find similarities with previous observations and line these up in order to form a more complete model. This could very well become complicated by the fact that under normal circumstances the model is obscured with the hands (occlusion) of the user (Dos Santos, Grevenstuk & Wendrich, 2009-2010).

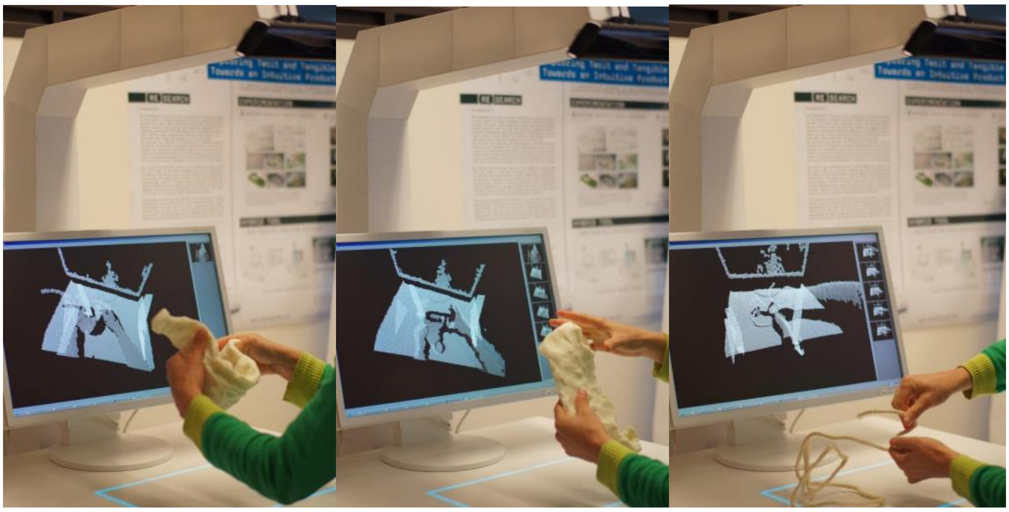


**Fig. 4-16** Prototype early phase RSFF-HDT - hybrid IA and representation

The result of this stage should be a 3-D point cloud or 3-D patch, in fairly high resolution. If all goes according to plan, the result of this stage is a grayscale map that shows the estimated distance of areas to a camera, i.e. brighter areas are closer to the camera (the exact brightness-to-depth mapping can vary) (Fig. 4-15 and Fig. 4-16).

### 4.3.4 3-D model representation and visualization

Once the model is available in 3-D data, it should be visualized. In order to see the 3-D effect, the visualization should at least show a rotating model, although it is preferable for the user to take control of the camera position etc.

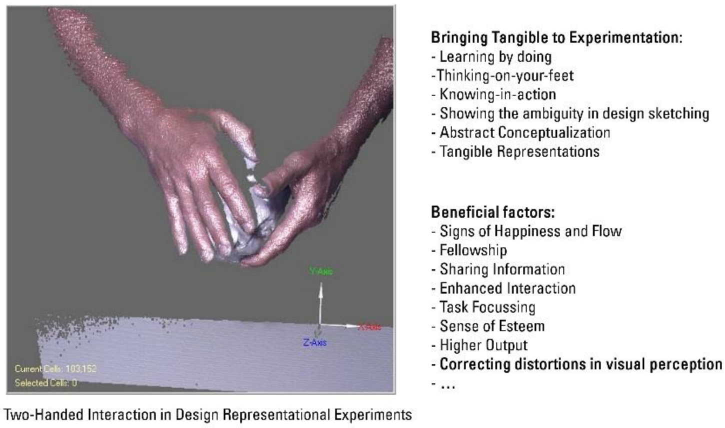



**Fig. 4-17** Bi-manual interaction and representation

At this point there is a need for a 3-D visualization tool, which can be as simple or complicated as needed. We feel that open source 3-D engine (e.g openSceneGraph, visualization library, ogre) could be of use, as this is once again a fairly complicated system and possibly quite costly to build and develop. Future versions could have a tighter integration with the underlying model, and allow direct manipulation in various forms. The final result should be a window with an interactive 3-D model of the observed artefact in real-time or near real-time (Fig. 4-17) (Dos Santos, Grevenstuk & Wendrich, 2009-2010).

### 4.3.5 Preliminary Conclusion

In our research experiments and tool testing in real world case studies, we observed highly-motivated users having virtually no trouble handling the user-interface while exploring the possibilities of the tool simultaneously manipulating real-world materials, objects and tools to visualize and represent their ideas and abstract notions. The tools offer an empathic and elegant solution for externalization of creativity and ideation wherein the user-in-the-loop feels in control, intuits manipulation of the interface and objects to trigger inspiration and imagination (Wendrich, 2010-2016).

We have authored, build and tested our prototypes in a variety of embodiments and architectures. All are based on the hybrid approach and underlying framework. Our initial attempt in 2009 to research and develop (R&D) a full-fledged RSFF-HDT system (https://vimeo.com/43850666) fell short in terms of realization, robustness, limitations and usability aspects. This was mainly due to the state-of-the-art (SOTA) in processing power (CPU), memory capacity, available hi-end visualization technologies and high costs in acquisition and development in both software and hardware components at the time (Wendrich, 2010-2016).

Finally, the hybrid approach to integrate existing and new advances in HCI, problem-solving, decision-making, mind-mapping, afford universal cross-domain access in conjunction with multi-disciplinary areas calls for a mere calm, empathic, and, holistic approach in the now and near future. To think about technologies, however, you have to learn to think as if you're already living in the future (Lanier, 2010).

# CONCLUSION

The analysis and evaluation of the seven representational experiments resulted in more insight, understanding and knowledge about;

- 3-D interaction and modelling
- 3-D visual- and tangible representation
- idiosyncratic interpretation and iteration
- abstract- and material representation
- bi-manual interaction and observation
- tacit-tangible manifestation

We aimed in this study to measure the representational effectiveness, performance speed, user engagement and other intrinsic qualities of various tangible-haptic representation techniques. We gathered knowledge on thresholds and learning curves, the implications of tool- and material constraints that could lead to stall, routines, flow and intuitive interactions. We observed a plethora in gestural (inter-) actions and a great variety in the differentiation of quality in skills, execution speed, and (implicit and explicit) knowledge during the execution of the seven experiments. In most cases participants showed fluency, focus, and wit, however with the gradual increase of embedding computational tools in the experiments, we noticed emergent inertia and entropy in user behaviour and –interaction. In some cases the participants gave up or asked for more time to finalize the design task. Conclusive findings and observations from the seven experiments based on the RQ are as follows:

1. Paper + Pencil (X1): Fast iteration and speedy execution of design task. The experiment description did not mention the designer to aim for highly detailed drawings, though the pencil and paper medium allowed for a lot more detail. This detailing pointed the facilitator to interrupt the experiment and terminate or extend (in later experiments) the session.
2. Sand + Pen (X2): Superfast iteration and speedy execution of design task. During Sand sketching the processing frequently becomes 'hindered' by the randomly moving sand kernels. However, this encouraged faster iteration and intuitive interaction from the participants.
3. Steam + Pen (X3): Superfast iteration and speedy execution of design task. This test had to be executed very quickly and with speed in interaction. To make a representation on the mirror covered with steam is a real challenge, because the continuous flow of steam constantly erased the earlier drawing lines. However, this triggered the intuitive interaction and speed of execution. The quality and level of detailing became of less interest, which in turn lead to more iterations over time.
4. Sand + Hands + Spatula (X4): Quick and easy manipulation and shaping. The formable mass (form-sand) allows for fast and speedy iterations and stimulates the haptic senses, manual dexterity, touch receptors and sensorial imagination. Some wooden tools are being used during processing to allow the introduction of some detailing.
5. Wire + Hands + Pliers (X5): Slower iteration, reduction in execution speed. The combination of merging 3-D spatial information, interpretation and construction of 3-D wire frames seemed difficult. This was partly due to the material properties, the force feedback and direct manipulation of the aluminium wire created execution constraints

and stall. Most results are reduced and naive representations of the role model. We allowed extra time.

6. Solid Works + WIMP (X6): Slow iteration and high reduction in execution speed and process flow. The overall scope in results of this test are considered outliers in terms of interaction, execution, quality and performance rate. The results are extremely poor in aesthetic quality, detailing, and naive in representation due to the required workflow procedure of the program and the relative low expertise levels of the participants. In all cases we allowed extra time.
7. ClayTools + Phantom Omni (X7): Very slow iteration and high reduction in execution speed and process flow. Overall the results are somewhat better than the X6 testbed, this is partly due to the ‘freeform nature’ of this sculpt and shape modality. Overall final results clearly show crude and raw interpretations of the role model whereby the constraints of the tool including the force-feedback from the haptic device had major influence and impact on the execution and detail level.

Although a facilitator was present and of support during all the experimentation sessions technological challenges often disrupted the process flow and directly influenced the performance speed and quality of the end results. Even though we predefined, aligned, and corrected possible bias and/or foreseeable stall in the individual experiments beforehand, the increase and effects of stall due to the tool threshold (steep learning curve) and/or program direction was highly significant and notable. The trend lines presented in Figure 3-1 clearly show these effects and how those affected the participant’s individual execution process time and process flow per experiment.

According to our research results and findings, the use of tangibles in the early design phase is key to design processing and the development of a HDT(E) (See Chapter 4). In order to use tangibles for physical interaction, the manipulations of these tangibles are to be translated and alternated into real-time representations of a virtual model. Reflection, incubation and learning are encouraged when technology is supportive and calm, it allows user-control, engagement and fosters learning skills while harnessing talent the HDT(E) is a full-loop system, which is used to generate both physical and virtual models. The type of deformations and manipulations on both models depend amongst others on the technology used to acquire data.

Our hybrid approach constitutes on the exploration and experimental tradition where we rely on an assortment of heuristics and operate mostly in a highly unpredictable, stochastic and/or probabilistic manner across boundaries and often un-structured approaches. The oscillation between real and virtual realities merges the autonomy of user and machine this will progressively enrich the intuitive user experience, increase knowledge acquisition, and advance insight in understanding.

# FUTURE WORK

Future research towards 3-D interaction (IA) with HDT (E)'s is necessary, as well as research into enhanced interaction (IxD) through for example automatic emotion recognition (AER), convolutional neural networks (CNN), and other emergent methods and fit-to-purpose technologies (i.e. sensors, ubiquity, web based). Primarily focused to detect 'creative slowdown', engage user behaviour, foster skill learning and pleasantly nudge during PCP's and PEP's. Based on the aforesaid, we focus and direct future research on:

- Robust web based (i.e. HTML5/CSS3) HDT 's (incl. an array of mixed- and augmented sensorial modalities and interfaces).
- Social-virtual reality networked HDT 's (incl. repositories, databases, API's etc.).
- Real-time web based 2-D and 3-D oscillating RSFF system (incl. 3-D AM process capabilities).

# REFERENCES

Alexander, C., (1964). Notes on the Synthesis of Form (Vol. 5). Harvard University Press.

Anderson, J. R., (1983). A spreading activation theory of memory. Journal of verbal learning and verbal behaviour, 22(3), 261-295. https://doi.org/10.1016/S0022-5371(83)90201-3

Bolter, J. D, Grusin, R., (2000). Remediation, Understanding New Media, Cambridge, MIT Press.

Bowers, K. S., & Hilgard, E. R. (1988). Some complexities in understanding memory.

Brereton, M., (2004). Distributed cognition in engineering design: negotiating between abstract and material representations. Design Representation, eds. by G. Goldschmidt and W.L. Porter. https://doi.org/10.1007/978-1-85233-863-3_4

Bruner, J. S., (1961). The act of discovery. Harvard educational review.

Bruner, J. S., (1965). The process of education. The Physics Teacher, 3(8), 369-370. https://doi.org/10.1119/1.2349211

Csikszentmihalyi, M., (1990). Flow: The psychology of optimal performance. NY: Cambridge University Press.

Dos Santos, G., Grevenstuk O., and Wendrich, R.E., (2009-2010). Technical Report, RAWSHAPE Rough Design. University of Twente, the Netherlands.

Dreyfus, H. L., Dreyfus, S. E., & Athanasiou, T. (1986). Mind over machine: the power of human intuition and expertise in the era of the computer. New York: Free Press.

Gigerenzer, G., (2007). Gut feeling. Viking, London.

Gilles, W., (1991). Form Organisation. Oxford: Butterworth-Heinemann Ltd.

Goldschmidt, G. and Porter, W., (2004). Design Representation. London, Springer. https://doi.org/10.1007/b97667

Grunwald, M. ed., (2008). Human haptic perception: Basics and applications. Springer Science & Business Media. https://doi.org/10.1007/978-3-7643-7612-3

Hartson, R., (2003). Cognitive, physical, sensory, and functional affordances in interaction design. Behaviour & Information Technology, 22(5), pp. 315-338. https://doi.org/10.1080/01449290310001592587

Jordan, B. and Henderson, A., (1995). Interaction analysis: Foundations and practice. The Journal of the Learning Sciences 4(1), pp. 39-103. https://doi.org/10.1207/s15327809jls0401_2

Kahneman, D., & Tversky, A., (1974). Judgment under uncertainty: Heuristics and biases. science, 185(4157), 1124-1131.

Klein, G., (1998). Sources of Power: How people make Decisions. Cambridge, MA: The MIT Press.

Lehrer, J., (2009). The decisive moment: how the brain makes up its mind. Canongate Books, Edinburgh, England.

McCullough, M, (1996). Abstracting craft: the practiced digital hand [PB book]. Cambridge, Mass. MIT Press. ISBN: 978-0-262-63189-X

Mednick, S., (1962). The associative basis of the creative process. Psychological review, 69(3), 220. https://doi.org/10.1037/h0048850

Meehl, P. E., (1957). When shall we use our heads instead of the formula? Journal of Counselling Psychology, 4(4), 268. https://doi.org/10.1037/h0047554

Miller, C. C., & Ireland, R. D. (2005). Intuition in strategic decision making: friend or foe in the fast-paced 21st century? The Academy of Management Executive, 19(1), 19-30.

Mlodinow, L., (2009). The drunkard's walk: How randomness rules our lives. Pantheon Books, New York, USA, 2009.

Nisbett, R. E., Krantz, D. H., Jepson, C., & Kunda, Z. (1983). The use of statistical heuristics in everyday inductive reasoning. Psychological Review, 90(4), 339. https://doi.org/10.1037/0033-295X.90.4.339

Polanyi, M., (1966). The tacit dimension. Chicago and London. The University of Chicago Press. ISBN-13:978-0-226-67298-4

Reichenbach, H., (1938). Experience and prediction: An analysis of the foundations and the structure of knowledge.

Ross, L., (1977). The Intuitive Psychologist and His Shortcomings: Distortions in the Attribution Process1. In Advances in experimental social psychology (Vol. 10, pp. 173-220). Academic Press. https://doi.org/10.1016/S0065-2601(08)60357-3

Schön, D. A., (1983). The reflective practitioner: How professionals think in action (Vol. 5126). Basic books.

Schön, D., (1992). Designing as Reflective Conversation with the Materials of a Design Situation. Research in Engineering Design: Volume 3, Number 3: Springer London. https://doi.org/10.1007/BF01580516

Sener, B., (2007). Rethinking digital industrial design: a mandate for virtual workshops and intelligent environments. Digital Creativity, 18(4), pp. 193-206. https://doi.org/10.1080/14626260701743192

Sener, B., & Pedgley, O., (2008). Novel multimodal interaction for industrial design. INTECH Open Access Publisher. https://doi.org/10.5772/6300

Simon, H.A., (1983). Search and reasoning in problem solving. Artificial intelligence, 21(1-2), pp 7-29. https://doi.org/10.1016/S0004-3702(83)80003-4

Simonton, D. K., (1988). Scientific genius: A psychology of science. New York: Cambridge University Press.

Thaler, R., & Sunstein, C., (2008). Nudge: The gentle power of choice architecture. New Haven, Conn.: Yale.

Truex, D. P., Baskerville, R., & Klein, H., (1999). Growing systems in emergent organizations. Communications of the ACM, 42(8), pp. 117-123. https://doi.org/10.1145/310930.310984

Wendrich, R.E., Tideman, M., (2004). Technology Scan on Virtual Form Giving in Higher Education Management of Technology, University of Twente. Available at http://www.rawshaping.com

Wendrich R.E., Tragter, H., Kokkeler, F.G.M., van Houten, F.J.A.M. (2009). Bridging the Design Gap: Towards an Intuitive Design Tool.

Wendrich R.E., (2010). Raw Shaping Form Finding: Tacit Tangible CAD. Sequin C.H. (ed.), Computer Aided Design & Applications, 7(4), 2010, 505-531. https://doi.org/10.3722/cadaps.2010.505-531

Wendrich R.E., van Houten F.J.A.M. (2010) Exploring Tacit and Tangible Interaction Design: Towards an Intuitive Design Tool. Proceedings of Virtual Reality International Conference, 7-9 April 2010, Laval, France.

Wendrich R.E., (2013). Hybrid Design Thinking in a Consummate Marriage of People and Technology. Sugiyama, K. (Ed.) In 5th International Congress of International Association of Societies of Design Research (IASDR), Tokyo, JPN.

Woolley, M., (2004). The Thoughtful Mark Maker - Representational Design Skills in the Post-information Age. In Design, Springer London, Representation, pp. 185-201. https://doi.org/10.1007/978-1-85233-863-3_8

Westcott, M. R., (1968). Toward a contemporary psychology of intuition: A historical, theoretical, and empirical inquiry. Holt, Rinehart and Winston.

Worthen, J. B., & Hunt, R. R., (2011). Mnemonology: Mnemonics for the 21st century. Psychology Press.

# APPENDIX

## A – X1 spread sheets (Pencil & paper)

**Table X1-3** final numerical results (ranked by time & quality combined)

| Group Rank | Rank A. Expert | Rank A. Advanced | Rank A. Novice | Rank All | Normalised Rank | No.: | Expertise Level: | X1 Avg. iter. time: | Total Average | Time limit |
|---|---|---|---|---|---|---|---|---|---|---|
| [1] | 1 | | | 1 | 0 | X1-22 | expert | 1:36 | 3:24 | 5:00 |
| [1] | 2 | | | 2 | 0.04 | X1-03 | expert | 1:50 | 3:24 | 5:00 |
| [1] | 3 | | | 3 | 0.08 | X1-25 | expert | 1:58 | 3:24 | 5:00 |
| [1] | 4 | | | 4 | 0.13 | X1-15 | expert | 2:03 | 3:24 | 5:00 |
| [2] | | | 1 | 5 | 0.17 | X1-07 | novice | 3:07 | 3:24 | 5:00 |
| [3] | | 1 | | 6 | 0.21 | X1-10 | advanced | 2:46 | 3:24 | 5:00 |
| [2] | | | 2 | 7 | 0.25 | X1-21 | novice | 2:06 | 3:24 | 5:00 |
| [2] | | | 3 | 8 | 0.29 | X1-08 | novice | 2:44 | 3:24 | 5:00 |
| [2] | | | 4 | 9 | 0.33 | X1-09 | novice | 2:09 | 3:24 | 5:00 |
| [3] | | 2 | | 10 | 0.38 | X1-05 | advanced | 3:45 | 3:24 | 5:00 |
| [2] | | | 5 | 11 | 0.42 | X1-12 | novice | 4:23 | 3:24 | 5:00 |
| [2] | | | 6 | 12 | 0.46 | X1-06 | novice | 2:21 | 3:24 | 5:00 |
| [2] | | | 7 | 13 | 0.50 | X1-13 | novice | 3:56 | 3:24 | 5:00 |
| [2] | | | 8 | 14 | 0.54 | X1-24 | novice | 2:29 | 3:24 | 5:00 |
| [1] | 5 | | | 15 | 0.58 | X1-02 | expert | 2:14 | 3:24 | 5:00 |
| [2] | | | 9 | 16 | 0.63 | X1-17 | novice | 4:13 | 3:24 | 5:00 |
| [2] | | | 10 | 17 | 0.67 | X1-14 | novice | 5:02 | 3:24 | 5:00 |
| [2] | | | 11 | 18 | 0.71 | X1-01 | novice | 2:25 | 3:24 | 5:00 |
| [2] | | | 12 | 19 | 0.75 | X1-11 | novice | 3:17 | 3:24 | 5:00 |
| [2] | | | 13 | 20 | 0.79 | X1-18 | novice | 6:42 | 3:24 | 5:00 |
| [2] | | | 14 | 21 | 0.83 | X1-20 | novice | 3:31 | 3:24 | 5:00 |
| [3] | | 3 | | 22 | 0.88 | X1-04 | advanced | 4:52 | 3:24 | 5:00 |
| [2] | | | 15 | 23 | 0.92 | X1-23 | novice | 5:19 | 3:24 | 5:00 |
| [2] | | | 16 | 24 | 0.96 | X1-16 | novice | 6:08 | 3:24 | 5:00 |
| [3] | | 4 | | 25 | 1 | X1-19 | advanced | 4:15 | 3:24 | 5:00 |
| | | | | | | | | [m:ss] | [m:ss] | [m:ss] |

**Table X1-4** final numerical results (ranked by time)

| | Rank T. Expert | Rank T. Advanced | Rank T. Novice | Rank T. | Normalised Rank T. | No.: | Expertise Level: | X1 Avg. iter. time: | Total Average | Time limit |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | | | 1 | 0 | X1-22 | expert | 1:36 | 3:24 | 5:00 |
| | 2 | | | 2 | 0.04 | X1-03 | expert | 1:50 | 3:24 | 5:00 |
| | 3 | | | 3 | 0.08 | X1-25 | expert | 1:58 | 3:24 | 5:00 |
| | 4 | | | 4 | 0.13 | X1-15 | expert | 2:03 | 3:24 | 5:00 |
| | | | 1 | 5 | 0.17 | X1-21 | novice | 2:06 | 3:24 | 5:00 |
| | | | 2 | 6 | 0.21 | X1-09 | novice | 2:09 | 3:24 | 5:00 |
| | 5 | | | 7 | 0.25 | X1-02 | expert | 2:14 | 3:24 | 5:00 |
| | | | 3 | 8 | 0.29 | X1-06 | novice | 2:21 | 3:24 | 5:00 |
| | | | 4 | 9 | 0.33 | X1-01 | novice | 2:25 | 3:24 | 5:00 |
| | | | 5 | 10 | 0.38 | X1-24 | novice | 2:29 | 3:24 | 5:00 |
| | | | 6 | 11 | 0.42 | X1-08 | novice | 2:44 | 3:24 | 5:00 |
| | | 1 | | 12 | 0.46 | X1-10 | advanced | 2:46 | 3:24 | 5:00 |
| | | | 7 | 13 | 0.50 | X1-07 | novice | 3:07 | 3:24 | 5:00 |
| | | | 8 | 14 | 0.54 | X1-11 | novice | 3:17 | 3:24 | 5:00 |
| | | | 9 | 15 | 0.58 | X1-20 | novice | 3:31 | 3:24 | 5:00 |
| | | 2 | | 16 | 0.63 | X1-05 | advanced | 3:45 | 3:24 | 5:00 |
| | | | 10 | 17 | 0.67 | X1-13 | novice | 3:56 | 3:24 | 5:00 |
| | | | 11 | 18 | 0.71 | X1-17 | novice | 4:13 | 3:24 | 5:00 |
| | | 3 | | 19 | 0.75 | X1-19 | advanced | 4:15 | 3:24 | 5:00 |
| | | | 12 | 20 | 0.79 | X1-12 | novice | 4:23 | 3:24 | 5:00 |
| | | 4 | | 21 | 0.83 | X1-04 | advanced | 4:52 | 3:24 | 5:00 |
| | | | 13 | 22 | 0.88 | X1-14 | novice | 5:02 | 3:24 | 5:00 |
| | | | 14 | 23 | 0.92 | X1-23 | novice | 5:19 | 3:24 | 5:00 |
| | | | 15 | 24 | 0.96 | X1-16 | novice | 6:08 | 3:24 | 5:00 |
| | | | 16 | 25 | 1 | X1-18 | novice | 6:42 | 3:24 | 5:00 |
| | | | | | | | | [m:ss] | [m:ss] | [m:ss] |

**Table X1-5** final numerical results (ranked by quality)

| | Rank Q. Expert | Rank Q. Advanced | Rank Q. Novice | Rank Q. | Normalised Rank Q. | No.: | Expertise Level: | X1 Avg. iter. time: | Total Average | Time limit |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1 | 1 | 0 | X1-07 | novice | 3:07 | 3:24 | 5:00 |
| | 1 | | | 2 | 0.04 | X1-22 | expert | 1:36 | 3:24 | 5:00 |
| | | 1 | | 3 | 0.08 | X1-10 | advanced | 2:46 | 3:24 | 5:00 |
| | 3 | | | 4 | 0.13 | X1-25 | expert | 1:58 | 3:24 | 5:00 |
| | 2 | | | 5 | 0.17 | X1-03 | expert | 1:50 | 3:24 | 5:00 |
| | | | 2 | 6 | 0.21 | X1-12 | novice | 4:23 | 3:24 | 5:00 |
| | | | 3 | 7 | 0.25 | X1-08 | novice | 2:44 | 3:24 | 5:00 |
| | 4 | | | 8 | 0.29 | X1-15 | expert | 2:03 | 3:24 | 5:00 |
| | | 2 | | 9 | 0.33 | X1-05 | advanced | 3:45 | 3:24 | 5:00 |
| | | | 4 | 10 | 0.38 | X1-14 | novice | 5:02 | 3:24 | 5:00 |
| | | | 5 | 11 | 0.42 | X1-13 | novice | 3:56 | 3:24 | 5:00 |
| | | | 6 | 12 | 0.46 | X1-18 | novice | 6:42 | 3:24 | 5:00 |
| | | | 7 | 13 | 0.50 | X1-21 | novice | 2:06 | 3:24 | 5:00 |
| | | | 8 | 14 | 0.54 | X1-17 | novice | 4:13 | 3:24 | 5:00 |
| | | | 9 | 15 | 0.58 | X1-09 | novice | 2:09 | 3:24 | 5:00 |
| | | | 10 | 16 | 0.63 | X1-16 | novice | 6:08 | 3:24 | 5:00 |
| | | | 11 | 17 | 0.67 | X1-23 | novice | 5:19 | 3:24 | 5:00 |
| | | 3 | | 18 | 0.71 | X1-04 | advanced | 4:52 | 3:24 | 5:00 |
| | | | 12 | 19 | 0.75 | X1-06 | novice | 2:21 | 3:24 | 5:00 |
| | | | 13 | 20 | 0.79 | X1-11 | novice | 3:17 | 3:24 | 5:00 |
| | | | 14 | 21 | 0.83 | X1-24 | novice | 2:29 | 3:24 | 5:00 |
| | | 4 | | 22 | 0.88 | X1-19 | advanced | 4:15 | 3:24 | 5:00 |
| | | | 15 | 23 | 0.92 | X1-20 | novice | 3:31 | 3:24 | 5:00 |
| | | | 16 | 24 | 0.96 | X1-01 | novice | 2:25 | 3:24 | 5:00 |
| | 5 | | | 25 | 1 | X1-02 | expert | 2:14 | 3:24 | 5:00 |
| | | | | | | | | [m:ss] | [m:ss] | [m:ss] |

# A – X2 spread sheets (Sand sketching)

**Table X2-3** final numerical results (ranked by time & quality combined)

| Group Rank | Rank A. Expert | Rank A. Advanced | Rank A. Novice | Rank All | Normalised Rank | No.: | Expertise Level: | X2 Avg. iter. time: | Total Average | Time limit |
|---|---|---|---|---|---|---|---|---|---|---|
| [1] | 1 | | | 1 | 0 | X2-38 | expert | 1:33 | 1:46 | 5:00 |
| [1] | 2 | | | 2 | 0.03 | X2-32 | expert | 1:15 | 1:46 | 5:00 |
| [1] | 3 | | | 3 | 0.05 | X2-34 | expert | 1:21 | 1:46 | 5:00 |
| [2] | | | 1 | 4 | 0.08 | X2-15 | novice | 1:32 | 1:46 | 5:00 |
| [2] | | | 2 | 5 | 0.11 | X2-03 | novice | 1:34 | 1:46 | 5:00 |
| [1] | 4 | | | 6 | 0.14 | X2-10 | expert | 1:49 | 1:46 | 5:00 |
| [2] | | | 3 | 7 | 0.16 | X2-08 | novice | 1:18 | 1:46 | 5:00 |
| [3] | | 1 | | 8 | 0.19 | X2-06 | advanced | 1:57 | 1:46 | 5:00 |
| [2] | | | 4 | 9 | 0.22 | X2-21 | novice | 0:44 | 1:46 | 5:00 |
| [2] | | | 5 | 10 | 0.24 | X2-31 | novice | 1:36 | 1:46 | 5:00 |
| [1] | 5 | | | 11 | 0.27 | X2-29 | expert | 1:04 | 1:46 | 5:00 |
| [2] | | | 6 | 12 | 0.30 | X2-02 | novice | 1:03 | 1:46 | 5:00 |
| [1] | 6 | | | 13 | 0.32 | X2-04 | expert | 2:14 | 1:46 | 5:00 |
| [2] | | | 7 | 14 | 0.35 | X2-13 | novice | 0:55 | 1:46 | 5:00 |
| [1] | 7 | | | 15 | 0.38 | X2-37 | expert | 1:49 | 1:46 | 5:00 |
| [2] | | | 8 | 16 | 0.41 | X2-16 | novice | 1:09 | 1:46 | 5:00 |
| [2] | | | 9 | 17 | 0.43 | X2-14 | novice | 0:36 | 1:46 | 5:00 |
| [2] | | | 10 | 18 | 0.46 | X2-17 | novice | 1:07 | 1:46 | 5:00 |
| [2] | | | 11 | 19 | 0.49 | X2-28 | novice | 0:52 | 1:46 | 5:00 |
| [2] | | | 12 | 20 | 0.51 | X2-27 | novice | 2:32 | 1:46 | 5:00 |
| [3] | | 2 | | 21 | 0.54 | X2-33 | advanced | 1:59 | 1:46 | 5:00 |
| [1] | 8 | | | 22 | 0.57 | X2-36 | expert | 2:31 | 1:46 | 5:00 |
| [2] | | | 13 | 23 | 0.59 | X2-35 | novice | 2:00 | 1:46 | 5:00 |
| [2] | | | 14 | 24 | 0.62 | X2-07 | novice | 2:18 | 1:46 | 5:00 |
| [3] | | 3 | | 25 | 0.65 | X2-26 | advanced | 1:26 | 1:46 | 5:00 |
| [2] | | | 15 | 26 | 0.68 | X2-30 | novice | 1:32 | 1:46 | 5:00 |
| [2] | | | 16 | 27 | 0.70 | X2-19 | novice | 2:06 | 1:46 | 5:00 |
| [2] | | | 17 | 28 | 0.73 | X2-09 | novice | 1:37 | 1:46 | 5:00 |
| [2] | | | 18 | 29 | 0.76 | X2-18 | novice | 1:48 | 1:46 | 5:00 |
| [2] | | | 19 | 30 | 0.78 | X2-11 | novice | 2:32 | 1:46 | 5:00 |
| [2] | | | 20 | 31 | 0.81 | X2-23 | novice | 2:58 | 1:46 | 5:00 |
| [2] | | | 21 | 32 | 0.84 | X2-25 | novice | 1:58 | 1:46 | 5:00 |
| [2] | | | 22 | 33 | 0.86 | X2-20 | novice | 2:09 | 1:46 | 5:00 |
| [2] | | | 23 | 34 | 0.89 | X2-24 | novice | 2:21 | 1:46 | 5:00 |
| [3] | | 4 | | 35 | 0.92 | X2-05 | advanced | 2:27 | 1:46 | 5:00 |
| [2] | | | 24 | 36 | 0.95 | X2-01 | novice | 3:14 | 1:46 | 5:00 |
| [2] | | | 25 | 37 | 0.97 | X2-12 | novice | 2:21 | 1:46 | 5:00 |
| [2] | | | 26 | 38 | 1 | X2-22 | novice | 2:24 | 1:46 | 5:00 |
| | | | | | | | | [m:ss] | [m:ss] | [m:ss] |

**Table X2-4** final numerical results (ranked by time)

| | Rank T. Expert | Rank T. Advanced | Rank T. Novice | Rank T. | Normalised Rank T. | No.: | Expertise Level: | X2 Avg. iter. time: | Total Average | Time limit |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1 | 1 | 0 | X2-14 | novice | 0:36 | 1:46 | 5:00 |
| | | | 2 | 2 | 0.03 | X2-21 | novice | 0:44 | 1:46 | 5:00 |
| | | | 3 | 3 | 0.05 | X2-28 | novice | 0:52 | 1:46 | 5:00 |
| | | | 4 | 4 | 0.08 | X2-13 | novice | 0:55 | 1:46 | 5:00 |
| | | | 5 | 5 | 0.11 | X2-02 | novice | 1:03 | 1:46 | 5:00 |
| | 1 | | | 6 | 0.14 | X2-29 | expert | 1:04 | 1:46 | 5:00 |
| | | | 6 | 7 | 0.16 | X2-17 | novice | 1:07 | 1:46 | 5:00 |
| | | | 7 | 8 | 0.19 | X2-16 | novice | 1:09 | 1:46 | 5:00 |
| | 2 | | | 9 | 0.22 | X2-32 | expert | 1:15 | 1:46 | 5:00 |
| | | | 8 | 10 | 0.24 | X2-08 | novice | 1:18 | 1:46 | 5:00 |
| | 3 | | | 11 | 0.27 | X2-34 | expert | 1:21 | 1:46 | 5:00 |
| | | 1 | | 12 | 0.30 | X2-26 | advanced | 1:26 | 1:46 | 5:00 |
| | | | 9 | 13 | 0.32 | X2-15 | novice | 1:32 | 1:46 | 5:00 |
| | | | 10 | 13 | 0.35 | X2-30 | novice | 1:32 | 1:46 | 5:00 |
| | 4 | | | 15 | 0.38 | X2-38 | expert | 1:33 | 1:46 | 5:00 |
| | | | 11 | 16 | 0.41 | X2-03 | novice | 1:34 | 1:46 | 5:00 |
| | | | 12 | 17 | 0.43 | X2-31 | novice | 1:36 | 1:46 | 5:00 |
| | | | 13 | 18 | 0.46 | X2-09 | novice | 1:37 | 1:46 | 5:00 |
| | | | 14 | 19 | 0.49 | X2-18 | novice | 1:48 | 1:46 | 5:00 |
| | 5 | | | 20 | 0.51 | X2-10 | expert | 1:49 | 1:46 | 5:00 |
| | 6 | | | 21 | 0.54 | X2-37 | expert | 1:49 | 1:46 | 5:00 |
| | | 2 | | 22 | 0.57 | X2-06 | advanced | 1:57 | 1:46 | 5:00 |
| | | | 15 | 23 | 0.59 | X2-25 | novice | 1:58 | 1:46 | 5:00 |
| | | 3 | | 24 | 0.62 | X2-33 | advanced | 1:59 | 1:46 | 5:00 |
| | | | 16 | 25 | 0.65 | X2-35 | novice | 2:00 | 1:46 | 5:00 |
| | | | 17 | 26 | 0.68 | X2-19 | novice | 2:06 | 1:46 | 5:00 |
| | | | 18 | 27 | 0.70 | X2-20 | novice | 2:09 | 1:46 | 5:00 |
| | 7 | | | 28 | 0.73 | X2-04 | expert | 2:14 | 1:46 | 5:00 |
| | | | 19 | 29 | 0.76 | X2-07 | novice | 2:18 | 1:46 | 5:00 |
| | | | 20 | 30 | 0.78 | X2-24 | novice | 2:21 | 1:46 | 5:00 |
| | | | 21 | 31 | 0.81 | X2-12 | novice | 2:21 | 1:46 | 5:00 |
| | | | 22 | 32 | 0.84 | X2-22 | novice | 2:24 | 1:46 | 5:00 |
| | | 4 | | 33 | 0.86 | X2-05 | advanced | 2:27 | 1:46 | 5:00 |
| | 8 | | | 34 | 0.89 | X2-36 | expert | 2:31 | 1:46 | 5:00 |
| | | | 23 | 35 | 0.92 | X2-11 | novice | 2:32 | 1:46 | 5:00 |
| | | | 24 | 36 | 0.95 | X2-27 | novice | 2:32 | 1:46 | 5:00 |
| | | | 25 | 37 | 0.97 | X2-23 | novice | 2:58 | 1:46 | 5:00 |
| | | | 26 | 38 | 1 | X2-01 | novice | 3:14 | 1:46 | 5:00 |
| | | | | | | | | [m:ss] | [m:ss] | [m:ss] |

**Table X2-5** final numerical results (ranked by quality)

| | Rank Q. Expert | Rank Q. Advanced | Rank Q. Novice | Rank Q. | Normalised Rank Q. | No.: | Expertise Level: | X2 Avg. iter. time: | Total Average | Time limit |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | | | 1 | 0 | X2-38 | expert | 1:33 | 1:46 | 5:00 |
| | 2 | | | 2 | 0.03 | X2-10 | expert | 1:49 | 1:46 | 5:00 |
| | 3 | | | 3 | 0.05 | X2-04 | expert | 2:14 | 1:46 | 5:00 |
| | | 1 | | 4 | 0.08 | X2-06 | advanced | 1:57 | 1:46 | 5:00 |
| | | | 1 | 5 | 0.11 | X2-27 | novice | 2:32 | 1:46 | 5:00 |
| | | | 2 | 6 | 0.14 | X2-03 | novice | 1:34 | 1:46 | 5:00 |
| | 4 | | | 7 | 0.16 | X2-34 | expert | 1:21 | 1:46 | 5:00 |
| | | | 3 | 8 | 0.19 | X2-15 | novice | 1:32 | 1:46 | 5:00 |
| | 5 | | | 9 | 0.22 | X2-32 | expert | 1:15 | 1:46 | 5:00 |
| | 6 | | | 10 | 0.24 | X2-36 | expert | 2:31 | 1:46 | 5:00 |
| | | | 4 | 11 | 0.27 | X2-31 | novice | 1:36 | 1:46 | 5:00 |
| | | | 5 | 12 | 0.30 | X2-23 | novice | 2:58 | 1:46 | 5:00 |
| | 7 | | | 13 | 0.32 | X2-37 | expert | 1:49 | 1:46 | 5:00 |
| | | | 6 | 14 | 0.35 | X2-11 | novice | 2:32 | 1:46 | 5:00 |
| | | | 7 | 15 | 0.38 | X2-08 | novice | 1:18 | 1:46 | 5:00 |
| | | | 8 | 16 | 0.41 | X2-01 | novice | 3:14 | 1:46 | 5:00 |
| | | | 9 | 17 | 0.43 | X2-07 | novice | 2:18 | 1:46 | 5:00 |
| | | 2 | | 18 | 0.46 | X2-05 | advanced | 2:27 | 1:46 | 5:00 |
| | | 3 | | 19 | 0.49 | X2-33 | advanced | 1:59 | 1:46 | 5:00 |
| | | | 10 | 20 | 0.51 | X2-35 | novice | 2:00 | 1:46 | 5:00 |
| | | | 11 | 21 | 0.54 | X2-24 | novice | 2:21 | 1:46 | 5:00 |
| | | | 12 | 22 | 0.57 | X2-19 | novice | 2:06 | 1:46 | 5:00 |
| | 8 | | | 23 | 0.59 | X2-29 | expert | 1:04 | 1:46 | 5:00 |
| | | | 13 | 24 | 0.62 | X2-20 | novice | 2:09 | 1:46 | 5:00 |
| | | | 14 | 25 | 0.65 | X2-02 | novice | 1:03 | 1:46 | 5:00 |
| | | | 15 | 26 | 0.68 | X2-21 | novice | 0:44 | 1:46 | 5:00 |
| | | | 16 | 27 | 0.70 | X2-16 | novice | 1:09 | 1:46 | 5:00 |
| | | | 17 | 28 | 0.73 | X2-25 | novice | 1:58 | 1:46 | 5:00 |
| | | | 18 | 29 | 0.76 | X2-13 | novice | 0:55 | 1:46 | 5:00 |
| | | | 19 | 30 | 0.78 | X2-18 | novice | 1:48 | 1:46 | 5:00 |
| | | | 20 | 31 | 0.81 | X2-09 | novice | 1:37 | 1:46 | 5:00 |
| | | | 21 | 32 | 0.84 | X2-17 | novice | 1:07 | 1:46 | 5:00 |
| | | | 22 | 33 | 0.86 | X2-22 | novice | 2:24 | 1:46 | 5:00 |
| | | | 23 | 34 | 0.89 | X2-12 | novice | 2:21 | 1:46 | 5:00 |
| | | | 24 | 35 | 0.92 | X2-30 | novice | 1:32 | 1:46 | 5:00 |
| | | 4 | | 36 | 0.95 | X2-26 | advanced | 1:26 | 1:46 | 5:00 |
| | | | 25 | 37 | 0.97 | X2-14 | novice | 0:36 | 1:46 | 5:00 |
| | | | 26 | 38 | 1 | X2-28 | novice | 0:52 | 1:46 | 5:00 |
| | | | | | | | | [m:ss] | [m:ss] | [m:ss] |

# A – X3 spread sheets (Steam sketching)

**Table X3-3** final numerical results (ranked by time & quality combined)

| Group Rank | Rank A. Expert | Rank A. Advanced | Rank A. Novice | Rank All | Normalised Rank | No.: | Expertise Level: | X3 Avg. iter. time: | Total Average | Time limit |
|---|---|---|---|---|---|---|---|---|---|---|
| [2] | | 1 | | 1 | 0 | X3-16 | advanced | 0:43 | 1:25 | 5:00 |
| [1] | 1 | | | 2 | 0.03 | X3-37 | expert | 0:45 | 1:25 | 5:00 |
| [1] | 2 | | | 3 | 0.05 | X3-27 | expert | 0:53 | 1:25 | 5:00 |
| [1] | 3 | | | 4 | 0.08 | X3-40 | expert | 0:57 | 1:25 | 5:00 |
| [2] | | 2 | | 5 | 0.10 | X3-26 | advanced | 0:38 | 1:25 | 5:00 |
| [3] | | | 1 | 6 | 0.13 | X3-01 | novice | 0:51 | 1:25 | 5:00 |
| [1] | 4 | | | 7 | 0.15 | X3-29 | expert | 1:04 | 1:25 | 5:00 |
| [3] | | | 2 | 8 | 0.18 | X3-05 | novice | 1:25 | 1:25 | 5:00 |
| [3] | | | 3 | 9 | 0.21 | X3-19 | novice | 1:12 | 1:25 | 5:00 |
| [1] | 5 | | | 10 | 0.23 | X3-31 | expert | 1:21 | 1:25 | 5:00 |
| [1] | 6 | | | 11 | 0.26 | X3-38 | expert | 0:49 | 1:25 | 5:00 |
| [1] | 7 | | | 12 | 0.28 | X3-32 | expert | 1:32 | 1:25 | 5:00 |
| [3] | | | 4 | 13 | 0.31 | X3-18 | novice | 1:18 | 1:25 | 5:00 |
| [3] | | | 5 | 14 | 0.33 | X3-07 | novice | 1:29 | 1:25 | 5:00 |
| [3] | | | 6 | 15 | 0.36 | X3-12 | novice | 0:55 | 1:25 | 5:00 |
| [3] | | | 7 | 16 | 0.38 | X3-02 | novice | 1:16 | 1:25 | 5:00 |
| [2] | | 3 | | 17 | 0.41 | X3-21 | advanced | 0:35 | 1:25 | 5:00 |
| [3] | | | 8 | 18 | 0.44 | X3-04 | novice | 1:39 | 1:25 | 5:00 |
| [1] | 8 | | | 19 | 0.46 | X3-24 | expert | 1:07 | 1:25 | 5:00 |
| [3] | | | 9 | 20 | 0.49 | X3-34 | novice | 0:58 | 1:25 | 5:00 |
| [3] | | | 10 | 21 | 0.51 | X3-03 | novice | 1:53 | 1:25 | 5:00 |
| [3] | | | 11 | 22 | 0.54 | X3-08 | novice | 1:02 | 1:25 | 5:00 |
| [3] | | | 12 | 23 | 0.56 | X3-25 | novice | 1:13 | 1:25 | 5:00 |
| [3] | | | 13 | 24 | 0.59 | X3-33 | novice | 1:00 | 1:25 | 5:00 |
| [3] | | | 14 | 25 | 0.62 | X3-35 | novice | 1:00 | 1:25 | 5:00 |
| [2] | | 4 | | 26 | 0.64 | X3-28 | advanced | 1:33 | 1:25 | 5:00 |
| [2] | | 5 | | 27 | 0.67 | X3-39 | advanced | 2:00 | 1:25 | 5:00 |
| [3] | | | 15 | 28 | 0.69 | X3-30 | novice | 1:17 | 1:25 | 5:00 |
| [2] | | 6 | | 29 | 0.72 | X3-17 | advanced | 1:30 | 1:25 | 5:00 |
| [3] | | | 16 | 30 | 0.74 | X3-06 | novice | 1:05 | 1:25 | 5:00 |
| [3] | | | 17 | 31 | 0.77 | X3-13 | novice | 1:06 | 1:25 | 5:00 |
| [3] | | | 18 | 32 | 0.79 | X3-14 | novice | 2:28 | 1:25 | 5:00 |
| [3] | | | 19 | 33 | 0.82 | X3-22 | novice | 2:36 | 1:25 | 5:00 |
| [3] | | | 20 | 34 | 0.85 | X3-20 | novice | 2:09 | 1:25 | 5:00 |
| [3] | | | 21 | 35 | 0.87 | X3-23 | novice | 2:30 | 1:25 | 5:00 |
| [2] | | 7 | | 36 | 0.90 | X3-36 | advanced | 2:31 | 1:25 | 5:00 |
| [3] | | | 22 | 37 | 0.92 | X3-10 | novice | 1:35 | 1:25 | 5:00 |
| [3] | | | 23 | 38 | 0.95 | X3-09 | novice | 2:23 | 1:25 | 5:00 |
| [3] | | | 24 | 39 | 0.97 | X3-11 | novice | 2:12 | 1:25 | 5:00 |
| [3] | | | 25 | 40 | 1 | X3-15 | novice | 2:48 | 1:25 | 5:00 |
| | | | | | | | | [m:ss] | [m:ss] | [m:ss] |

**Table X3-4** final numerical results (ranked by time)

| | Rank T. Expert | Rank T. Advanced | Rank T. Novice | Rank T. | Normalised Rank T. | No.: | Expertise Level: | X3 Avg. iter. time: | Total Average | Time limit |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | | 1 | 0 | X3-21 | advanced | 0:35 | 1:25 | 5:00 |
| | | 2 | | 2 | 0.03 | X3-26 | advanced | 0:38 | 1:25 | 5:00 |
| | | 3 | | 3 | 0.05 | X3-16 | advanced | 0:43 | 1:25 | 5:00 |
| | 1 | | | 4 | 0.08 | X3-37 | expert | 0:45 | 1:25 | 5:00 |
| | 2 | | | 5 | 0.10 | X3-38 | expert | 0:49 | 1:25 | 5:00 |
| | | | 1 | 6 | 0.13 | X3-01 | novice | 0:51 | 1:25 | 5:00 |
| | 3 | | | 7 | 0.15 | X3-27 | expert | 0:53 | 1:25 | 5:00 |
| | | | 2 | 8 | 0.18 | X3-12 | novice | 0:55 | 1:25 | 5:00 |
| | 4 | | | 9 | 0.21 | X3-40 | expert | 0:57 | 1:25 | 5:00 |
| | | | 3 | 10 | 0.23 | X3-34 | novice | 0:58 | 1:25 | 5:00 |
| | | | 4 | 11 | 0.26 | X3-33 | novice | 1:00 | 1:25 | 5:00 |
| | | | 5 | 12 | 0.28 | X3-35 | novice | 1:00 | 1:25 | 5:00 |
| | | | 6 | 13 | 0.31 | X3-08 | novice | 1:02 | 1:25 | 5:00 |
| | 5 | | | 14 | 0.33 | X3-29 | expert | 1:04 | 1:25 | 5:00 |
| | | | 7 | 15 | 0.36 | X3-06 | novice | 1:05 | 1:25 | 5:00 |
| | | | 8 | 16 | 0.38 | X3-13 | novice | 1:06 | 1:25 | 5:00 |
| | 6 | | | 17 | 0.41 | X3-24 | expert | 1:07 | 1:25 | 5:00 |
| | | | 9 | 18 | 0.44 | X3-19 | novice | 1:12 | 1:25 | 5:00 |
| | | | 10 | 19 | 0.46 | X3-25 | novice | 1:13 | 1:25 | 5:00 |
| | | | 11 | 20 | 0.49 | X3-02 | novice | 1:16 | 1:25 | 5:00 |
| | | | 12 | 21 | 0.51 | X3-30 | novice | 1:17 | 1:25 | 5:00 |
| | | | 13 | 22 | 0.54 | X3-18 | novice | 1:18 | 1:25 | 5:00 |
| | 7 | | | 23 | 0.56 | X3-31 | expert | 1:21 | 1:25 | 5:00 |
| | | | 14 | 24 | 0.59 | X3-05 | novice | 1:25 | 1:25 | 5:00 |
| | | | 15 | 25 | 0.62 | X3-07 | novice | 1:29 | 1:25 | 5:00 |
| | | 4 | | 26 | 0.64 | X3-17 | advanced | 1:30 | 1:25 | 5:00 |
| | 8 | | | 27 | 0.67 | X3-32 | expert | 1:32 | 1:25 | 5:00 |
| | | 5 | | 28 | 0.69 | X3-28 | advanced | 1:33 | 1:25 | 5:00 |
| | | | 16 | 29 | 0.72 | X3-10 | novice | 1:35 | 1:25 | 5:00 |
| | | | 17 | 30 | 0.74 | X3-04 | novice | 1:39 | 1:25 | 5:00 |
| | | | 18 | 31 | 0.77 | X3-03 | novice | 1:53 | 1:25 | 5:00 |
| | | 6 | | 32 | 0.79 | X3-39 | advanced | 2:00 | 1:25 | 5:00 |
| | | | 19 | 33 | 0.82 | X3-20 | novice | 2:09 | 1:25 | 5:00 |
| | | | 20 | 34 | 0.85 | X3-11 | novice | 2:12 | 1:25 | 5:00 |
| | | | 21 | 35 | 0.87 | X3-09 | novice | 2:23 | 1:25 | 5:00 |
| | | | 22 | 36 | 0.90 | X3-14 | novice | 2:28 | 1:25 | 5:00 |
| | | | 23 | 37 | 0.92 | X3-23 | novice | 2:30 | 1:25 | 5:00 |
| | | 7 | | 38 | 0.95 | X3-36 | advanced | 2:31 | 1:25 | 5:00 |
| | | | 24 | 39 | 0.97 | X3-22 | novice | 2:36 | 1:25 | 5:00 |
| | | | 25 | 40 | 1 | X3-15 | novice | 2:48 | 1:25 | 5:00 |
| | | | | | | | | [m:ss] | [m:ss] | [m:ss] |

**Table X3-5** final numerical results (ranked by quality)

| | Rank Q. Expert | Rank Q. Advanced | Rank Q. Novice | Rank Q. | Normalised Rank Q. | No.: | Expertise Level: | X3 Avg. iter. time: | Total Average | Time limit |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | | | 1 | 0 | X3-40 | expert | 0:57 | 1:25 | 5:00 |
| | | 1 | | 2 | 0.03 | X3-16 | advanced | 0:43 | 1:25 | 5:00 |
| | 2 | | | 3 | 0.05 | X3-27 | expert | 0:53 | 1:25 | 5:00 |
| | | | 1 | 4 | 0.08 | X3-05 | novice | 1:25 | 1:25 | 5:00 |
| | 3 | | | 5 | 0.10 | X3-37 | expert | 0:45 | 1:25 | 5:00 |
| | 4 | | | 6 | 0.13 | X3-32 | expert | 1:32 | 1:25 | 5:00 |
| | 5 | | | 7 | 0.15 | X3-29 | expert | 1:04 | 1:25 | 5:00 |
| | 6 | | | 8 | 0.18 | X3-31 | expert | 1:21 | 1:25 | 5:00 |
| | | | 2 | 9 | 0.21 | X3-04 | novice | 1:39 | 1:25 | 5:00 |
| | | | 3 | 10 | 0.23 | X3-03 | novice | 1:53 | 1:25 | 5:00 |
| | | | 4 | 11 | 0.26 | X3-07 | novice | 1:29 | 1:25 | 5:00 |
| | | 2 | | 12 | 0.28 | X3-39 | advanced | 2:00 | 1:25 | 5:00 |
| | | | 5 | 13 | 0.31 | X3-19 | novice | 1:12 | 1:25 | 5:00 |
| | | | 6 | 14 | 0.33 | X3-18 | novice | 1:18 | 1:25 | 5:00 |
| | | | 7 | 15 | 0.36 | X3-01 | novice | 0:51 | 1:25 | 5:00 |
| | | 3 | | 16 | 0.38 | X3-28 | advanced | 1:33 | 1:25 | 5:00 |
| | | | 8 | 17 | 0.41 | X3-02 | novice | 1:16 | 1:25 | 5:00 |
| | | | 9 | 18 | 0.44 | X3-22 | novice | 2:36 | 1:25 | 5:00 |
| | | 4 | | 19 | 0.46 | X3-26 | advanced | 0:38 | 1:25 | 5:00 |
| | | | 10 | 20 | 0.49 | X3-14 | novice | 2:28 | 1:25 | 5:00 |
| | | 5 | | 21 | 0.51 | X3-17 | advanced | 1:30 | 1:25 | 5:00 |
| | | | 11 | 22 | 0.54 | X3-23 | novice | 2:30 | 1:25 | 5:00 |
| | 7 | | | 23 | 0.56 | X3-24 | expert | 1:07 | 1:25 | 5:00 |
| | | | 12 | 24 | 0.59 | X3-25 | novice | 1:13 | 1:25 | 5:00 |
| | | | 13 | 25 | 0.62 | X3-30 | novice | 1:17 | 1:25 | 5:00 |
| | | | 14 | 26 | 0.64 | X3-20 | novice | 2:09 | 1:25 | 5:00 |
| | 8 | | | 27 | 0.67 | X3-38 | expert | 0:49 | 1:25 | 5:00 |
| | | 6 | | 28 | 0.69 | X3-36 | advanced | 2:31 | 1:25 | 5:00 |
| | | | 15 | 29 | 0.72 | X3-12 | novice | 0:55 | 1:25 | 5:00 |
| | | | 16 | 30 | 0.74 | X3-08 | novice | 1:02 | 1:25 | 5:00 |
| | | | 17 | 31 | 0.77 | X3-34 | novice | 0:58 | 1:25 | 5:00 |
| | | | 18 | 32 | 0.79 | X3-35 | novice | 1:00 | 1:25 | 5:00 |
| | | | 19 | 33 | 0.82 | X3-33 | novice | 1:00 | 1:25 | 5:00 |
| | | | 20 | 34 | 0.85 | X3-06 | novice | 1:05 | 1:25 | 5:00 |
| | | | 21 | 35 | 0.87 | X3-15 | novice | 2:48 | 1:25 | 5:00 |
| | | | 22 | 36 | 0.90 | X3-09 | novice | 2:23 | 1:25 | 5:00 |
| | | 7 | | 37 | 0.92 | X3-21 | advanced | 0:35 | 1:25 | 5:00 |
| | | | 23 | 38 | 0.95 | X3-13 | novice | 1:06 | 1:25 | 5:00 |
| | | | 24 | 39 | 0.97 | X3-11 | novice | 2:12 | 1:25 | 5:00 |
| | | | 25 | 40 | 1 | X3-10 | novice | 1:35 | 1:25 | 5:00 |
| | | | | | | | | [m:ss] | [m:ss] | [m:ss] |

# A – X4 spread sheets (Sand sculpting)

**Table X4-3** final numerical results (ranked by time & quality combined)

| Group Rank | Rank A. Expert | Rank A. Advanced | Rank A. Novice | Rank All | Normalised Rank | No.: | Expertise Level: | X4 Avg. iter. time: | Total Average | Time limit |
|---|---|---|---|---|---|---|---|---|---|---|
| [1] | 1 | | | 1 | 0 | X4-30 | expert | 2:01 | 3:43 | 5:00 |
| [3] | | 1 | | 2 | 0.03 | X4-04 | advanced | 2:03 | 3:43 | 5:00 |
| [2] | | | 1 | 3 | 0.06 | X4-05 | novice | 3:21 | 3:43 | 5:00 |
| [3] | | 2 | | 4 | 0.09 | X4-11 | advanced | 2:52 | 3:43 | 5:00 |
| [1] | 2 | | | 5 | 0.12 | X4-10 | expert | 2:52 | 3:43 | 5:00 |
| [1] | 3 | | | 6 | 0.15 | X4-34 | expert | 3:13 | 3:43 | 5:00 |
| [1] | 4 | | | 7 | 0.18 | X4-07 | expert | 3:19 | 3:43 | 5:00 |
| [2] | | | 2 | 8 | 0.21 | X4-29 | novice | 2:39 | 3:43 | 5:00 |
| [2] | | | 3 | 9 | 0.24 | X4-18 | novice | 3:55 | 3:43 | 5:00 |
| [2] | | | 4 | 10 | 0.27 | X4-26 | novice | 3:10 | 3:43 | 5:00 |
| [2] | | | 5 | 11 | 0.30 | X4-31 | novice | 2:21 | 3:43 | 5:00 |
| [2] | | | 6 | 12 | 0.33 | X4-32 | novice | 2:41 | 3:43 | 5:00 |
| [1] | 5 | | | 13 | 0.36 | X4-20 | expert | 4:43 | 3:43 | 5:00 |
| [2] | | | 7 | 14 | 0.39 | X4-17 | novice | 4:39 | 3:43 | 5:00 |
| [2] | | | 8 | 15 | 0.42 | X4-13 | novice | 4:58 | 3:43 | 5:00 |
| [2] | | | 9 | 16 | 0.45 | X4-24 | novice | 2:23 | 3:43 | 5:00 |
| [2] | | | 10 | 17 | 0.48 | X4-03 | novice | 2:56 | 3:43 | 5:00 |
| [2] | | | 11 | 18 | 0.52 | X4-01 | novice | 2:43 | 3:43 | 5:00 |
| [3] | | 3 | | 19 | 0.55 | X4-21 | advanced | 3:20 | 3:43 | 5:00 |
| [2] | | | 12 | 20 | 0.58 | X4-27 | novice | 4:01 | 3:43 | 5:00 |
| [2] | | | 13 | 21 | 0.61 | X4-16 | novice | 2:42 | 3:43 | 5:00 |
| [2] | | | 14 | 22 | 0.64 | X4-06 | novice | 4:38 | 3:43 | 5:00 |
| [2] | | | 15 | 23 | 0.67 | X4-33 | novice | 2:47 | 3:43 | 5:00 |
| [3] | | 4 | | 24 | 0.70 | X4-19 | advanced | 4:23 | 3:43 | 5:00 |
| [3] | | 5 | | 25 | 0.73 | X4-22 | advanced | 4:21 | 3:43 | 5:00 |
| [2] | | | 16 | 26 | 0.76 | X4-02 | novice | 5:01 | 3:43 | 5:00 |
| [3] | | 6 | | 27 | 0.79 | X4-25 | advanced | 3:47 | 3:43 | 5:00 |
| [1] | 6 | | | 28 | 0.82 | X4-15 | expert | 5:25 | 3:43 | 5:00 |
| [2] | | | 17 | 29 | 0.85 | X4-28 | novice | 4:54 | 3:43 | 5:00 |
| [2] | | | 18 | 30 | 0.88 | X4-08 | novice | 3:47 | 3:43 | 5:00 |
| [1] | 7 | | | 31 | 0.91 | X4-12 | expert | 4:50 | 3:43 | 5:00 |
| [1] | 8 | | | 32 | 0.94 | X4-14 | expert | 5:01 | 3:43 | 5:00 |
| [3] | | 7 | | 33 | 0.97 | X4-23 | advanced | 5:18 | 3:43 | 5:00 |
| [2] | | | 19 | 34 | 1 | X4-09 | novice | 5:21 | 3:43 | 5:00 |
| | | | | | | | | [m:ss] | [m:ss] | [m:ss] |

**Table X4-4** final numerical results (ranked by time)

| | Rank T. Expert | Rank T. Advanced | Rank T. Novice | Rank T. | Normalised Rank T. | No.: | Expertise Level: | X4 Avg. iter. time: | Total Average | Time limit |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | | | 1 | 0 | X4-30 | expert | 2:01 | 3:43 | 5:00 |
| | | 1 | | 2 | 0.03 | X4-04 | advanced | 2:03 | 3:43 | 5:00 |
| | | | 1 | 3 | 0.06 | X4-31 | novice | 2:21 | 3:43 | 5:00 |
| | | | 2 | 4 | 0.09 | X4-24 | novice | 2:23 | 3:43 | 5:00 |
| | | | 3 | 5 | 0.12 | X4-29 | novice | 2:39 | 3:43 | 5:00 |
| | | | 4 | 6 | 0.15 | X4-32 | novice | 2:41 | 3:43 | 5:00 |
| | | | 5 | 7 | 0.18 | X4-16 | novice | 2:42 | 3:43 | 5:00 |
| | | | 6 | 8 | 0.21 | X4-01 | novice | 2:43 | 3:43 | 5:00 |
| | | | 7 | 9 | 0.24 | X4-33 | novice | 2:47 | 3:43 | 5:00 |
| | 2 | | | 10 | 0.27 | X4-10 | expert | 2:52 | 3:43 | 5:00 |
| | | 2 | | 11 | 0.30 | X4-11 | advanced | 2:52 | 3:43 | 5:00 |
| | | | 8 | 12 | 0.33 | X4-03 | novice | 2:56 | 3:43 | 5:00 |
| | | | 9 | 13 | 0.36 | X4-26 | novice | 3:10 | 3:43 | 5:00 |
| | 3 | | | 14 | 0.39 | X4-34 | expert | 3:13 | 3:43 | 5:00 |
| | 4 | | | 15 | 0.42 | X4-07 | expert | 3:19 | 3:43 | 5:00 |
| | | 3 | | 16 | 0.45 | X4-21 | advanced | 3:20 | 3:43 | 5:00 |
| | | | 10 | 17 | 0.48 | X4-05 | novice | 3:21 | 3:43 | 5:00 |
| | | | 11 | 18 | 0.52 | X4-08 | novice | 3:47 | 3:43 | 5:00 |
| | | 4 | | 19 | 0.55 | X4-25 | advanced | 3:47 | 3:43 | 5:00 |
| | | | 12 | 20 | 0.58 | X4-18 | novice | 3:55 | 3:43 | 5:00 |
| | | | 13 | 21 | 0.61 | X4-27 | novice | 4:01 | 3:43 | 5:00 |
| | | 5 | | 22 | 0.64 | X4-22 | advanced | 4:21 | 3:43 | 5:00 |
| | | 6 | | 23 | 0.67 | X4-19 | advanced | 4:23 | 3:43 | 5:00 |
| | | | 14 | 24 | 0.70 | X4-06 | novice | 4:38 | 3:43 | 5:00 |
| | | | 15 | 25 | 0.73 | X4-17 | novice | 4:39 | 3:43 | 5:00 |
| | 5 | | | 26 | 0.76 | X4-20 | expert | 4:43 | 3:43 | 5:00 |
| | 6 | | | 27 | 0.79 | X4-12 | expert | 4:50 | 3:43 | 5:00 |
| | | | 16 | 28 | 0.82 | X4-28 | novice | 4:54 | 3:43 | 5:00 |
| | | | 17 | 29 | 0.85 | X4-13 | novice | 4:58 | 3:43 | 5:00 |
| | | | 18 | 30 | 0.88 | X4-02 | novice | 5:01 | 3:43 | 5:00 |
| | 7 | | | 31 | 0.91 | X4-14 | expert | 5:01 | 3:43 | 5:00 |
| | | 7 | | 32 | 0.94 | X4-23 | advanced | 5:18 | 3:43 | 5:00 |
| | | | 19 | 33 | 0.97 | X4-09 | novice | 5:21 | 3:43 | 5:00 |
| | 8 | | | 34 | 1 | X4-15 | expert | 5:25 | 3:43 | 5:00 |
| | | | | | | | | [m:ss] | [m:ss] | [m:ss] |

**Table X4-5** final numerical results (ranked by quality)

| | Rank Q. Expert | Rank Q. Advanced | Rank Q. Novice | Rank Q. | Normalised Rank Q. | No.: | Expertise Level: | X4 Avg. iter. time: | Total Average | Time limit |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | | | 1 | 0 | X4-30 | expert | 2:01 | 3:43 | 5:00 |
| | | | 1 | 2 | 0.03 | X4-05 | novice | 3:21 | 3:43 | 5:00 |
| | | | 2 | 3 | 0.06 | X4-13 | novice | 4:58 | 3:43 | 5:00 |
| | 2 | | | 4 | 0.09 | X4-20 | expert | 4:43 | 3:43 | 5:00 |
| | | | 3 | 5 | 0.12 | X4-18 | novice | 3:55 | 3:43 | 5:00 |
| | | | 4 | 6 | 0.15 | X4-17 | novice | 4:39 | 3:43 | 5:00 |
| | 3 | | | 7 | 0.18 | X4-07 | expert | 3:19 | 3:43 | 5:00 |
| | 4 | | | 8 | 0.21 | X4-34 | expert | 3:13 | 3:43 | 5:00 |
| | | 1 | | 9 | 0.24 | X4-04 | advanced | 2:03 | 3:43 | 5:00 |
| | | 2 | | 10 | 0.27 | X4-11 | advanced | 2:52 | 3:43 | 5:00 |
| | 5 | | | 11 | 0.30 | X4-10 | expert | 2:52 | 3:43 | 5:00 |
| | | | 5 | 12 | 0.33 | X4-02 | novice | 5:01 | 3:43 | 5:00 |
| | | | 6 | 13 | 0.36 | X4-27 | novice | 4:01 | 3:43 | 5:00 |
| | 6 | | | 14 | 0.39 | X4-15 | expert | 5:25 | 3:43 | 5:00 |
| | | | 7 | 15 | 0.42 | X4-06 | novice | 4:38 | 3:43 | 5:00 |
| | | | 8 | 16 | 0.45 | X4-26 | novice | 3:10 | 3:43 | 5:00 |
| | | 3 | | 17 | 0.48 | X4-19 | advanced | 4:23 | 3:43 | 5:00 |
| | | 4 | | 18 | 0.52 | X4-21 | advanced | 3:20 | 3:43 | 5:00 |
| | | 5 | | 19 | 0.55 | X4-22 | advanced | 4:21 | 3:43 | 5:00 |
| | | | 9 | 20 | 0.58 | X4-29 | novice | 2:39 | 3:43 | 5:00 |
| | | | 10 | 21 | 0.61 | X4-03 | novice | 2:56 | 3:43 | 5:00 |
| | | | 11 | 22 | 0.64 | X4-28 | novice | 4:54 | 3:43 | 5:00 |
| | 7 | | | 23 | 0.67 | X4-14 | expert | 5:01 | 3:43 | 5:00 |
| | | | 12 | 24 | 0.70 | X4-32 | novice | 2:41 | 3:43 | 5:00 |
| | 8 | | | 25 | 0.73 | X4-12 | expert | 4:50 | 3:43 | 5:00 |
| | | | 13 | 26 | 0.76 | X4-01 | novice | 2:43 | 3:43 | 5:00 |
| | | | 14 | 27 | 0.79 | X4-31 | novice | 2:21 | 3:43 | 5:00 |
| | | 6 | | 28 | 0.82 | X4-23 | advanced | 5:18 | 3:43 | 5:00 |
| | | | 15 | 29 | 0.85 | X4-24 | novice | 2:23 | 3:43 | 5:00 |
| | | 7 | | 30 | 0.88 | X4-25 | advanced | 3:47 | 3:43 | 5:00 |
| | | | 16 | 31 | 0.91 | X4-33 | novice | 2:47 | 3:43 | 5:00 |
| | | | 17 | 32 | 0.94 | X4-16 | novice | 2:42 | 3:43 | 5:00 |
| | | | 18 | 33 | 0.97 | X4-09 | novice | 5:21 | 3:43 | 5:00 |
| | | | 19 | 34 | 1 | X4-08 | novice | 3:47 | 3:43 | 5:00 |
| | | | | | | | | [m:ss] | [m:ss] | [m:ss] |

# A – X5 spread sheets (Wire plying)

**Table X5-3** final numerical results (ranked by time & quality combined)

| Group Rank | Rank A. Expert | Rank A. Advanced | Rank A. Novice | Rank All | Normalised Rank | No.: | Expertise Level: | X5 Avg. iter. time: | Total Average | Time limit |
|---|---|---|---|---|---|---|---|---|---|---|
| [1] | | | 1 | 1 | 0 | X5-27 | novice | 5:28 | 6:49 | 5:00 |
| [2] | | 1 | | 2 | 0.04 | X5-10 | advanced | 5:16 | 6:49 | 5:00 |
| [2] | | 2 | | 3 | 0.07 | X5-20 | advanced | 5:31 | 6:49 | 5:00 |
| [1] | | | 2 | 4 | 0.11 | X5-25 | novice | 6:10 | 6:49 | 5:00 |
| [2] | | 3 | | 5 | 0.15 | X5-12 | advanced | 5:58 | 6:49 | 5:00 |
| [2] | | 4 | | 6 | 0.19 | X5-08 | advanced | 6:22 | 6:49 | 5:00 |
| [1] | | | 3 | 7 | 0.22 | X5-18 | novice | 6:33 | 6:49 | 5:00 |
| [2] | | 5 | | 8 | 0.26 | X5-07 | advanced | 5:24 | 6:49 | 5:00 |
| [3] | 1 | | | 9 | 0.30 | X5-23 | expert | 7:24 | 6:49 | 5:00 |
| [3] | 2 | | | 10 | 0.33 | X5-28 | expert | 7:45 | 6:49 | 5:00 |
| [1] | | | 4 | 11 | 0.37 | X5-16 | novice | 5:46 | 6:49 | 5:00 |
| [3] | 3 | | | 12 | 0.41 | X5-05 | expert | 7:41 | 6:49 | 5:00 |
| [1] | | | 5 | 13 | 0.44 | X5-11 | novice | 6:02 | 6:49 | 5:00 |
| [1] | | | 6 | 14 | 0.48 | X5-21 | novice | 6:33 | 6:49 | 5:00 |
| [1] | | | 7 | 15 | 0.52 | X5-19 | novice | 7:42 | 6:49 | 5:00 |
| [1] | | | 8 | 16 | 0.56 | X5-13 | novice | 7:29 | 6:49 | 5:00 |
| [2] | | 6 | | 17 | 0.59 | X5-09 | advanced | 6:28 | 6:49 | 5:00 |
| [1] | | | 9 | 18 | 0.63 | X5-01 | novice | 7:14 | 6:49 | 5:00 |
| [1] | | | 10 | 19 | 0.67 | X5-15 | novice | 8:57 | 6:49 | 5:00 |
| [1] | | | 11 | 20 | 0.70 | X5-17 | novice | 6:12 | 6:49 | 5:00 |
| [1] | | | 12 | 21 | 0.74 | X5-22 | novice | 6:54 | 6:49 | 5:00 |
| [1] | | | 13 | 22 | 0.78 | X5-24 | novice | 7:34 | 6:49 | 5:00 |
| [1] | | | 14 | 23 | 0.81 | X5-26 | novice | 7:28 | 6:49 | 5:00 |
| [2] | | 7 | | 24 | 0.85 | X5-04 | advanced | 6:51 | 6:49 | 5:00 |
| [1] | | | 15 | 25 | 0.89 | X5-03 | novice | 7:04 | 6:49 | 5:00 |
| [1] | | | 16 | 26 | 0.93 | X5-02 | novice | 7:46 | 6:49 | 5:00 |
| [1] | | | 17 | 27 | 0.96 | X5-14 | novice | 7:39 | 6:49 | 5:00 |
| [1] | | | 18 | 28 | 1 | X5-06 | novice | 8:07 | 6:49 | 5:00 |
| | | | | | | | | [m:ss] | [m:ss] | [m:ss] |

**Table X5-4** final numerical results (ranked by time)

| | Rank T. Expert | Rank T. Advanced | Rank T. Novice | Rank T. | Normalised Rank T. | No.: | Expertise Level: | X5 Avg. iter. time: | Total Average | Time limit |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | | 1 | 0 | X5-10 | advanced | 5:16 | 6:49 | 5:00 |
| | | 2 | | 2 | 0.04 | X5-07 | advanced | 5:24 | 6:49 | 5:00 |
| | | | 1 | 3 | 0.07 | X5-27 | novice | 5:28 | 6:49 | 5:00 |
| | | 3 | | 4 | 0.11 | X5-20 | advanced | 5:31 | 6:49 | 5:00 |
| | | | 2 | 5 | 0.15 | X5-16 | novice | 5:46 | 6:49 | 5:00 |
| | | 4 | | 6 | 0.19 | X5-12 | advanced | 5:58 | 6:49 | 5:00 |
| | | | 3 | 7 | 0.22 | X5-11 | novice | 6:02 | 6:49 | 5:00 |
| | | | 4 | 8 | 0.26 | X5-25 | novice | 6:10 | 6:49 | 5:00 |
| | | | 5 | 9 | 0.30 | X5-17 | novice | 6:12 | 6:49 | 5:00 |
| | | 5 | | 10 | 0.33 | X5-08 | advanced | 6:22 | 6:49 | 5:00 |
| | | 6 | | 11 | 0.37 | X5-09 | advanced | 6:28 | 6:49 | 5:00 |
| | | | 6 | 12 | 0.41 | X5-18 | novice | 6:33 | 6:49 | 5:00 |
| | | | 7 | 13 | 0.44 | X5-21 | novice | 6:33 | 6:49 | 5:00 |
| | | 7 | | 14 | 0.48 | X5-04 | advanced | 6:51 | 6:49 | 5:00 |
| | | | 8 | 15 | 0.52 | X5-22 | novice | 6:54 | 6:49 | 5:00 |
| | | | 9 | 16 | 0.56 | X5-03 | novice | 7:04 | 6:49 | 5:00 |
| | | | 10 | 17 | 0.59 | X5-01 | novice | 7:14 | 6:49 | 5:00 |
| | 1 | | | 18 | 0.63 | X5-23 | expert | 7:24 | 6:49 | 5:00 |
| | | | 11 | 19 | 0.67 | X5-26 | novice | 7:28 | 6:49 | 5:00 |
| | | | 12 | 20 | 0.70 | X5-13 | novice | 7:29 | 6:49 | 5:00 |
| | | | 13 | 21 | 0.74 | X5-24 | novice | 7:34 | 6:49 | 5:00 |
| | | | 14 | 22 | 0.78 | X5-14 | novice | 7:39 | 6:49 | 5:00 |
| | 2 | | | 23 | 0.81 | X5-05 | expert | 7:41 | 6:49 | 5:00 |
| | | | 15 | 24 | 0.85 | X5-19 | novice | 7:42 | 6:49 | 5:00 |
| | 3 | | | 25 | 0.89 | X5-28 | expert | 7:45 | 6:49 | 5:00 |
| | | | 16 | 26 | 0.93 | X5-02 | novice | 7:46 | 6:49 | 5:00 |
| | | | 17 | 27 | 0.96 | X5-06 | novice | 8:07 | 6:49 | 5:00 |
| | | | 18 | 28 | 1 | X5-15 | novice | 8:57 | 6:49 | 5:00 |
| | | | | | | | | [m:ss] | [m:ss] | [m:ss] |

**Table X5-5** final numerical results (ranked by quality)

| | Rank Q. Expert | Rank Q. Advanced | Rank Q. Novice | Rank Q. | Normalised Rank Q. | No.: | Expertise Level: | X5 Avg. iter. time: | Total Average | Time limit |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | | | 1 | 0 | X5-28 | expert | 7:45 | 6:49 | 5:00 |
| | 2 | | | 2 | 0.04 | X5-23 | expert | 7:24 | 6:49 | 5:00 |
| | | | 1 | 3 | 0.07 | X5-27 | novice | 5:28 | 6:49 | 5:00 |
| | 3 | | | 4 | 0.11 | X5-05 | expert | 7:41 | 6:49 | 5:00 |
| | | | 2 | 5 | 0.15 | X5-19 | novice | 7:42 | 6:49 | 5:00 |
| | | | 3 | 6 | 0.19 | X5-15 | novice | 8:57 | 6:49 | 5:00 |
| | | | 4 | 7 | 0.22 | X5-18 | novice | 6:33 | 6:49 | 5:00 |
| | | | 5 | 8 | 0.26 | X5-25 | novice | 6:10 | 6:49 | 5:00 |
| | | 1 | | 9 | 0.30 | X5-08 | advanced | 6:22 | 6:49 | 5:00 |
| | | | 6 | 10 | 0.33 | X5-13 | novice | 7:29 | 6:49 | 5:00 |
| | | 2 | | 11 | 0.37 | X5-10 | advanced | 5:16 | 6:49 | 5:00 |
| | | 3 | | 12 | 0.41 | X5-20 | advanced | 5:31 | 6:49 | 5:00 |
| | | 4 | | 13 | 0.44 | X5-12 | advanced | 5:58 | 6:49 | 5:00 |
| | | | 7 | 14 | 0.48 | X5-02 | novice | 7:46 | 6:49 | 5:00 |
| | | | 8 | 15 | 0.52 | X5-24 | novice | 7:34 | 6:49 | 5:00 |
| | | | 9 | 16 | 0.56 | X5-21 | novice | 6:33 | 6:49 | 5:00 |
| | | | 10 | 17 | 0.59 | X5-01 | novice | 7:14 | 6:49 | 5:00 |
| | | 5 | | 18 | 0.63 | X5-07 | advanced | 5:24 | 6:49 | 5:00 |
| | | | 11 | 19 | 0.67 | X5-26 | novice | 7:28 | 6:49 | 5:00 |
| | | | 12 | 20 | 0.70 | X5-22 | novice | 6:54 | 6:49 | 5:00 |
| | | | 13 | 21 | 0.74 | X5-11 | novice | 6:02 | 6:49 | 5:00 |
| | | | 14 | 22 | 0.78 | X5-16 | novice | 5:46 | 6:49 | 5:00 |
| | | 6 | | 23 | 0.81 | X5-09 | advanced | 6:28 | 6:49 | 5:00 |
| | | | 15 | 24 | 0.85 | X5-03 | novice | 7:04 | 6:49 | 5:00 |
| | | | | 25 | 0.89 | X5-04 | advanced | 6:51 | 6:49 | 5:00 |
| | | | 16 | 26 | 0.93 | X5-17 | novice | 6:12 | 6:49 | 5:00 |
| | | | 17 | 27 | 0.96 | X5-14 | novice | 7:39 | 6:49 | 5:00 |
| | | | 18 | 28 | 1 | X5-06 | novice | 8:07 | 6:49 | 5:00 |
| | | | | | | | | [m:ss] | [m:ss] | [m:ss] |

## A – X6 spread sheets (3-D CAD)

**Table X6-3** final results after calculations (ranked by time & quality combined)

| Group Rank | Rank A. Expert | Rank A. Advanced | Rank A. Novice | Rank All | Normalised Rank | No.: | Expertise Level: | X6 Avg. iter. time: | Total Average | Time limit |
|---|---|---|---|---|---|---|---|---|---|---|
| [2] | 1 | | | 1 | 0 | X6-03 | expert | 7:41 | 12:23 | 5:00 |
| [1] | | | 1 | 2 | 0.05 | X6-19 | novice | 8:14 | 12:23 | 5:00 |
| [1] | | | 2 | 3 | 0.10 | X6-11 | novice | 8:01 | 12:23 | 5:00 |
| [3] | | 1 | | 4 | 0.14 | X6-20 | advanced | 8:27 | 12:23 | 5:00 |
| [2] | 2 | | | 5 | 0.19 | X6-04 | expert | 8:51 | 12:23 | 5:00 |
| [2] | 3 | | | 6 | 0.24 | X6-10 | expert | 11:56 | 12:23 | 5:00 |
| [3] | | 2 | | 7 | 0.29 | X6-21 | advanced | 8:39 | 12:23 | 5:00 |
| [1] | | | 3 | 8 | 0.33 | X6-12 | novice | 16:50 | 12:23 | 5:00 |
| [1] | | | 4 | 9 | 0.38 | X6-14 | novice | 9:06 | 12:23 | 5:00 |
| [3] | | 3 | | 10 | 0.43 | X6-07 | advanced | 6:35 | 12:23 | 5:00 |
| [3] | | 4 | | 11 | 0.48 | X6-02 | advanced | 8:44 | 12:23 | 5:00 |
| [1] | | | 5 | 12 | 0.52 | X6-01 | novice | 8:47 | 12:23 | 5:00 |
| [1] | | | 6 | 13 | 0.57 | X6-15 | novice | 11:44 | 12:23 | 5:00 |
| [2] | 4 | | | 14 | 0.62 | X6-22 | expert | 26:12 | 12:23 | 5:00 |
| [1] | | | 7 | 15 | 0.67 | X6-09 | novice | 7:54 | 12:23 | 5:00 |
| [1] | | | 8 | 16 | 0.71 | X6-06 | novice | 26:38 | 12:23 | 5:00 |
| [1] | | | 9 | 17 | 0.76 | X6-18 | novice | 9:44 | 12:23 | 5:00 |
| [1] | | | 10 | 18 | 0.81 | X6-16 | novice | 15:13 | 12:23 | 5:00 |
| [3] | | 5 | | 19 | 0.86 | X6-13 | advanced | 13:35 | 12:23 | 5:00 |
| [1] | | | 11 | 20 | 0.90 | X6-17 | novice | 14:47 | 12:23 | 5:00 |
| [2] | 5 | | | 21 | 0.95 | X6-05 | expert | 19:18 | 12:23 | 5:00 |
| [1] | | | 12 | 22 | 1 | X6-08 | novice | 15:35 | 12:23 | 5:00 |
| | | | | | | | | [m:ss] | [m:ss] | [m:ss] |

**Table X6-4** final results after calculations (ranked by time)

| | Rank T. Expert | Rank T. Advanced | Rank T. Novice | Rank T. | Normalised Rank T. | No.: | Expertise Level: | X6 Avg. iter. time: | Total Average | Time limit |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | | 1 | 0 | X6-07 | advanced | 6:35 | 12:23 | 5:00 |
| | 1 | | | 2 | 0.05 | X6-03 | expert | 7:41 | 12:23 | 5:00 |
| | | | 1 | 3 | 0.10 | X6-09 | novice | 7:54 | 12:23 | 5:00 |
| | | | 2 | 4 | 0.14 | X6-11 | novice | 8:01 | 12:23 | 5:00 |
| | | | 3 | 5 | 0.19 | X6-19 | novice | 8:14 | 12:23 | 5:00 |
| | | 2 | | 6 | 0.24 | X6-20 | advanced | 8:27 | 12:23 | 5:00 |
| | | 3 | | 7 | 0.29 | X6-21 | advanced | 8:39 | 12:23 | 5:00 |
| | | 4 | | 8 | 0.33 | X6-02 | advanced | 8:44 | 12:23 | 5:00 |
| | | | 4 | 9 | 0.38 | X6-01 | novice | 8:47 | 12:23 | 5:00 |
| | 2 | | | 10 | 0.43 | X6-04 | expert | 8:51 | 12:23 | 5:00 |
| | | | 5 | 11 | 0.48 | X6-14 | novice | 9:06 | 12:23 | 5:00 |
| | | | 6 | 12 | 0.52 | X6-18 | novice | 9:44 | 12:23 | 5:00 |
| | | | 7 | 13 | 0.57 | X6-15 | novice | 11:44 | 12:23 | 5:00 |
| | 3 | | | 14 | 0.62 | X6-10 | expert | 11:56 | 12:23 | 5:00 |
| | | 5 | | 15 | 0.67 | X6-13 | advanced | 13:35 | 12:23 | 5:00 |
| | | | 8 | 16 | 0.71 | X6-17 | novice | 14:47 | 12:23 | 5:00 |
| | | | 9 | 17 | 0.76 | X6-16 | novice | 15:13 | 12:23 | 5:00 |
| | | | 10 | 18 | 0.81 | X6-08 | novice | 15:35 | 12:23 | 5:00 |
| | | | 11 | 19 | 0.86 | X6-12 | novice | 16:50 | 12:23 | 5:00 |
| | 4 | | | 20 | 0.90 | X6-05 | expert | 19:18 | 12:23 | 5:00 |
| | 5 | | | 21 | 0.95 | X6-22 | expert | 26:12 | 12:23 | 5:00 |
| | | | 12 | 22 | 1 | X6-06 | novice | 26:38 | 12:23 | 5:00 |
| | | | | | | | | [m:ss] | [m:ss] | [m:ss] |

**Table X6-5** final results after calculations (ranked by quality)

| | Rank Q. Expert | Rank Q. Advanced | Rank Q. Novice | Rank Q. | Normalised Rank Q. | No.: | Expertise Level: | X6 Avg. iter. time: | Total Average | Time limit |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1 | 1 | 0 | X6-12 | novice | *16:50* | 12:23 | 5:00 |
| | 1 | | | 2 | 0.05 | X6-10 | expert | *11:56* | 12:23 | 5:00 |
| | 2 | | | 3 | 0.10 | X6-22 | expert | *26:12* | 12:23 | 5:00 |
| | | | 2 | 4 | 0.14 | X6-06 | novice | *26:38* | 12:23 | 5:00 |
| | | | 3 | 5 | 0.19 | X6-19 | novice | *8:14* | 12:23 | 5:00 |
| | 3 | | | 6 | 0.24 | X6-04 | expert | *8:51* | 12:23 | 5:00 |
| | | | 4 | 7 | 0.29 | X6-11 | novice | *8:01* | 12:23 | 5:00 |
| | 4 | | | 8 | 0.33 | X6-03 | expert | *7:41* | 12:23 | 5:00 |
| | | 1 | | 9 | 0.38 | X6-20 | advanced | *8:27* | 12:23 | 5:00 |
| | | | 5 | 10 | 0.43 | X6-14 | novice | *9:06* | 12:23 | 5:00 |
| | | | 6 | 11 | 0.48 | X6-15 | novice | *11:44* | 12:23 | 5:00 |
| | | | 7 | 12 | 0.52 | X6-16 | novice | *15:13* | 12:23 | 5:00 |
| | | 2 | | 13 | 0.57 | X6-21 | advanced | *8:39* | 12:23 | 5:00 |
| | | 3 | | 14 | 0.62 | X6-02 | advanced | *8:44* | 12:23 | 5:00 |
| | | | 8 | 15 | 0.67 | X6-01 | novice | *8:47* | 12:23 | 5:00 |
| | 5 | | | 16 | 0.71 | X6-05 | expert | *19:18* | 12:23 | 5:00 |
| | | | 9 | 17 | 0.76 | X6-18 | novice | *9:44* | 12:23 | 5:00 |
| | | 4 | | 18 | 0.81 | X6-13 | advanced | *13:35* | 12:23 | 5:00 |
| | | | 10 | 19 | 0.86 | X6-17 | novice | *14:47* | 12:23 | 5:00 |
| | | | 11 | 20 | 0.90 | X6-08 | novice | *15:35* | 12:23 | 5:00 |
| | | 5 | | 21 | 0.95 | X6-07 | advanced | *6:35* | 12:23 | 5:00 |
| | | | 12 | 22 | 1 | X6-09 | novice | *7:54* | 12:23 | 5:00 |
| | | | | | | | | [m:ss] | [m:ss] | [m:ss] |

# A – X7 spread sheets (3-D Virtual clay)

**Table X7-3** final numerical results (ranked by time & quality combined)

| Group Rank | Rank A. Expert | Rank A. Advanced | Rank A. Novice | Rank All | Normalised Rank | No.: | Expertise Level: | X7 Avg. iter. time: | Total Average | Time limit |
|---|---|---|---|---|---|---|---|---|---|---|
| [1] | | | 1 | 1 | 0 | X7-09 | novice | 12:20 | 18:13 | 5:00 |
| [2] | 1 | | | 2 | 0.05 | X7-19 | expert | 17:39 | 18:13 | 5:00 |
| [3] | | 1 | | 3 | 0.10 | X7-01 | advanced | 9:29 | 18:13 | 5:00 |
| [1] | | | 2 | 4 | 0.15 | X7-04 | novice | 21:19 | 18:13 | 5:00 |
| [1] | | | 3 | 5 | 0.20 | X7-08 | novice | 10:43 | 18:13 | 5:00 |
| [1] | | | 4 | 6 | 0.25 | X7-05 | novice | 24:38 | 18:13 | 5:00 |
| [2] | 2 | | | 7 | 0.30 | X7-11 | expert | 14:06 | 18:13 | 5:00 |
| [1] | | | 5 | 8 | 0.35 | X7-10 | novice | 14:16 | 18:13 | 5:00 |
| [1] | | | 6 | 9 | 0.40 | X7-17 | novice | 16:34 | 18:13 | 5:00 |
| [1] | | | 7 | 10 | 0.45 | X7-16 | novice | 19:26 | 18:13 | 5:00 |
| [1] | | | 8 | 11 | 0.50 | X7-07 | novice | 10:43 | 18:13 | 5:00 |
| [3] | | 2 | | 12 | 0.55 | X7-21 | advanced | 19:53 | 18:13 | 5:00 |
| [3] | | 3 | | 13 | 0.60 | X7-13 | advanced | 19:30 | 18:13 | 5:00 |
| [1] | | | 9 | 14 | 0.65 | X7-03 | novice | 11:32 | 18:13 | 5:00 |
| [3] | | 4 | | 15 | 0.70 | X7-14 | advanced | 28:22 | 18:13 | 5:00 |
| [1] | | | 10 | 16 | 0.75 | X7-18 | novice | 19:05 | 18:13 | 5:00 |
| [1] | | | 11 | 17 | 0.80 | X7-06 | novice | 12:49 | 18:13 | 5:00 |
| [3] | | 5 | | 18 | 0.85 | X7-12 | advanced | 26:00 | 18:13 | 5:00 |
| [3] | | 6 | | 19 | 0.90 | X7-15 | advanced | 26:09 | 18:13 | 5:00 |
| [1] | | | 12 | 20 | 0.95 | X7-20 | novice | 29:57 | 18:13 | 5:00 |
| [2] | 3 | | | 21 | 1 | X7-02 | expert | - | 18:13 | 5:00 |
| | | | | | | | | [m:ss] | [m:ss] | [m:ss] |

**Table X7-4** final numerical results (ranked by time)

| | Rank T. Expert | Rank T. Advanced | Rank T. Novice | Rank T. | Normalised Rank T. | No.: | Expertise Level: | X7 Avg. iter. time: | Total Average | Time limit |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | | 1 | 0 | X7-01 | advanced | 9:29 | 18:13 | 5:00 |
| | | | 1 | 2 | 0.05 | X7-07 | novice | 10:43 | 18:13 | 5:00 |
| | | | 2 | 3 | 0.10 | X7-08 | novice | 10:43 | 18:13 | 5:00 |
| | | | 3 | 4 | 0.15 | X7-03 | novice | 11:32 | 18:13 | 5:00 |
| | | | 4 | 5 | 0.20 | X7-09 | novice | 12:20 | 18:13 | 5:00 |
| | | | 5 | 6 | 0.25 | X7-06 | novice | 12:49 | 18:13 | 5:00 |
| | 1 | | | 7 | 0.30 | X7-11 | expert | 14:06 | 18:13 | 5:00 |
| | | | 6 | 8 | 0.35 | X7-10 | novice | 14:16 | 18:13 | 5:00 |
| | | | 7 | 9 | 0.40 | X7-17 | novice | 16:34 | 18:13 | 5:00 |
| | 2 | | | 10 | 0.45 | X7-19 | expert | 17:39 | 18:13 | 5:00 |
| | | | 8 | 11 | 0.50 | X7-18 | novice | 19:05 | 18:13 | 5:00 |
| | | | 9 | 12 | 0.55 | X7-16 | novice | 19:26 | 18:13 | 5:00 |
| | | 2 | | 13 | 0.60 | X7-13 | advanced | 19:30 | 18:13 | 5:00 |
| | | 3 | | 14 | 0.65 | X7-21 | advanced | 19:53 | 18:13 | 5:00 |
| | | | 10 | 15 | 0.70 | X7-04 | novice | 21:19 | 18:13 | 5:00 |
| | | | 11 | 16 | 0.75 | X7-05 | novice | 24:38 | 18:13 | 5:00 |
| | | 4 | | 17 | 0.80 | X7-12 | advanced | 26:00 | 18:13 | 5:00 |
| | | 5 | | 18 | 0.85 | X7-15 | advanced | 26:09 | 18:13 | 5:00 |
| | | 6 | | 19 | 0.90 | X7-14 | advanced | 28:22 | 18:13 | 5:00 |
| | | | 12 | 20 | 0.95 | X7-20 | novice | 29:57 | 18:13 | 5:00 |
| | 3 | | | 21 | 1 | X7-02 | expert | - | 18:13 | 5:00 |
| | | | | | | | | [m:ss] | [m:ss] | [m:ss] |

**Table X7-5** final numerical results (ranked by quality)

| | Rank Q. Expert | Rank Q. Advanced | Rank Q. Novice | Rank Q. | Normalised Rank Q. | No.: | Expertise Level: | X7 Avg. iter. time: | Total Average | Time limit |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1 | 1 | 0 | X7-04 | novice | 21:19 | 18:13 | 5:00 |
| | | | 2 | 2 | 0.05 | X7-05 | novice | 24:38 | 18:13 | 5:00 |
| | | | 3 | 3 | 0.10 | X7-09 | novice | 12:20 | 18:13 | 5:00 |
| | 1 | | | 4 | 0.15 | X7-19 | expert | 17:39 | 18:13 | 5:00 |
| | | 1 | | 5 | 0.20 | X7-14 | advanced | 28:22 | 18:13 | 5:00 |
| | | 2 | | 6 | 0.25 | X7-21 | advanced | 19:53 | 18:13 | 5:00 |
| | | | 4 | 7 | 0.30 | X7-16 | novice | 19:26 | 18:13 | 5:00 |
| | | 3 | | 8 | 0.35 | X7-13 | advanced | 19:30 | 18:13 | 5:00 |
| | | 4 | | 9 | 0.40 | X7-12 | advanced | 26:00 | 18:13 | 5:00 |
| | | | 5 | 10 | 0.45 | X7-17 | novice | 16:34 | 18:13 | 5:00 |
| | | | 6 | 11 | 0.50 | X7-10 | novice | 14:16 | 18:13 | 5:00 |
| | 2 | | | 12 | 0.55 | X7-11 | expert | 14:06 | 18:13 | 5:00 |
| | | 5 | | 13 | 0.60 | X7-15 | advanced | 26:09 | 18:13 | 5:00 |
| | | | 7 | 14 | 0.65 | X7-18 | novice | 19:05 | 18:13 | 5:00 |
| | | 6 | | 15 | 0.70 | X7-01 | advanced | 9:29 | 18:13 | 5:00 |
| | | | 8 | 16 | 0.75 | X7-08 | novice | 10:43 | 18:13 | 5:00 |
| | | | 9 | 17 | 0.80 | X7-20 | novice | 29:57 | 18:13 | 5:00 |
| | | | 10 | 18 | 0.85 | X7-07 | novice | 10:43 | 18:13 | 5:00 |
| | | | 11 | 19 | 0.90 | X7-03 | novice | 11:32 | 18:13 | 5:00 |
| | | | 12 | 20 | 0.95 | X7-06 | novice | 12:49 | 18:13 | 5:00 |
| | 3 | | | 21 | 1 | X7-02 | expert | - | 18:13 | 5:00 |
| | | | | | | | | [m:ss] | [m:ss] | [m:ss] |

## B – Group rank results 1st, 2nd and 3rd

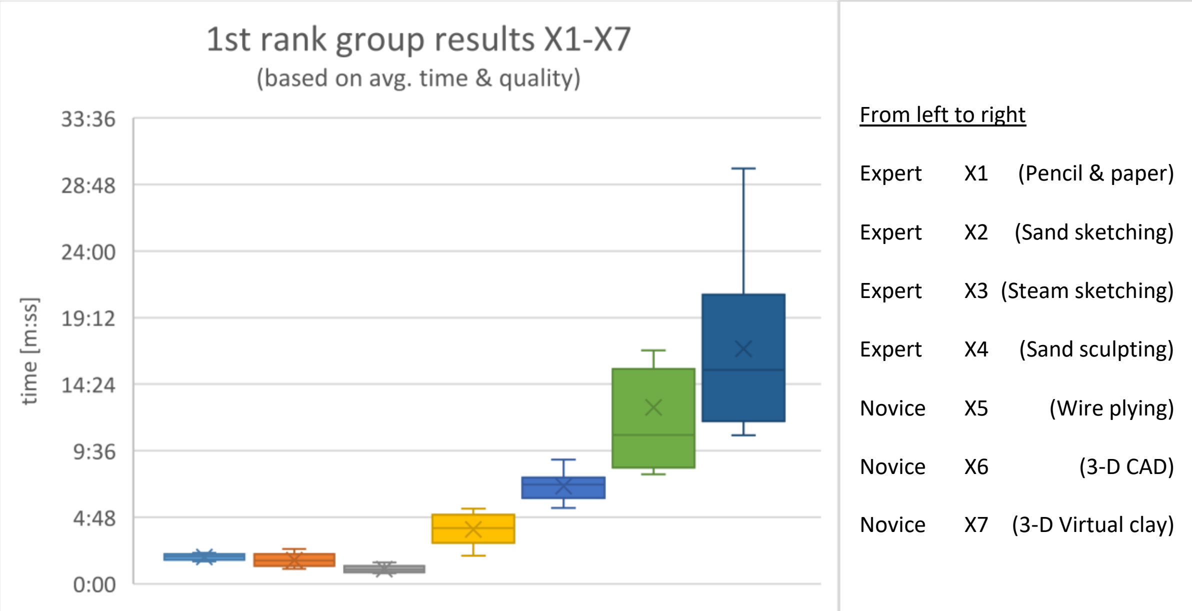



**Fig. 3-3** Best group per experiment (1st rank)

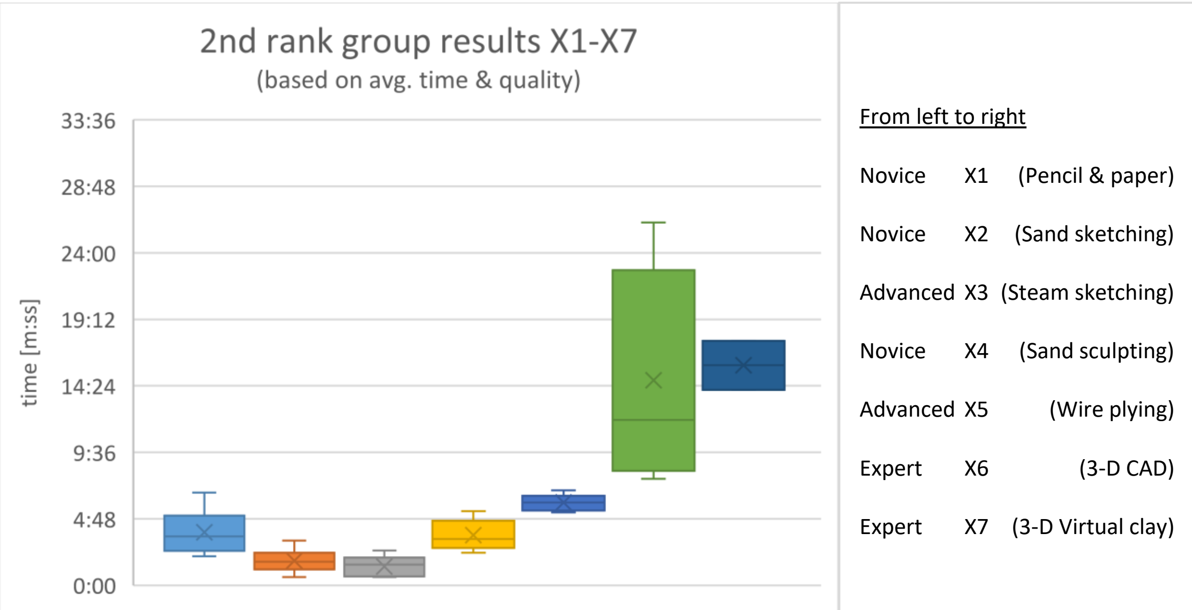
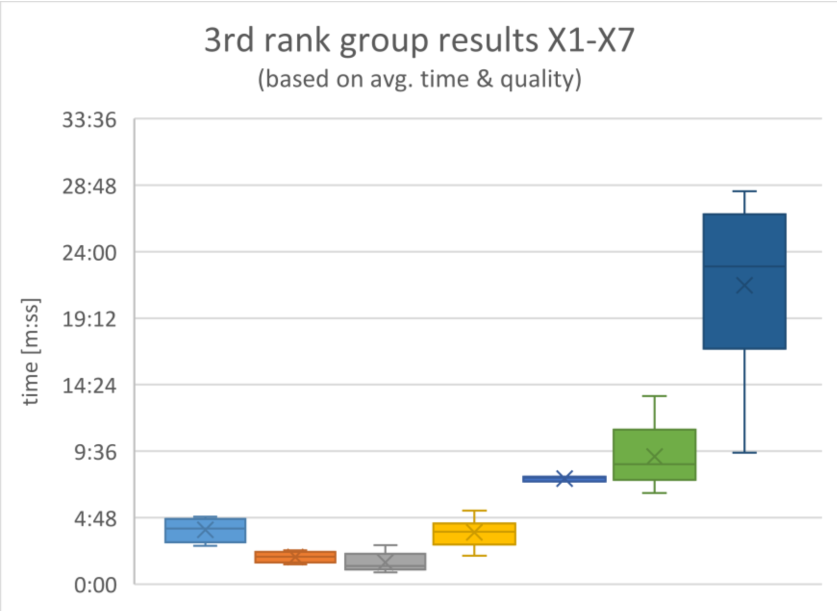



**Fig. 3-4** Second best group per experiment (2nd rank)




<u>From left to right</u>

Advanced X1 (Pencil & paper)

Advanced X2 (Sand sketching)

Novice X3 (Steam sketching)

Advanced X4 (Sand sculpting)

Expert X5 (Wire plying)

Advanced X6 (3-D CAD)

Advanced X7 (3-D Virtual clay)

**Fig. 3-5** Third group per experiment (3rd rank)

## C – Proposed base software

- c++
    - http://www.microsoft.com/express/Downloads/
- Video for Windows
- videoInput
    - http://muonics.net/school/spring05/videoInput/
- openCV
    - http://opencv.willowgarage.com/wiki/
- IVT
    - http://ivt.sourceforge.net/
- openscenegraph
    - http://www.openscenegraph.org/
- visualization library
    - http://www.visualizationlibrary.com/jetcms/
- ogre
    - http://www.ogre3d.com/
- Intel threading building blocks
    - http://www.threadingbuildingblocks.org/
- PoCo
    - http://pocoproject.org/
- boost
    - http://www.boost.org/