“Ah, I see what you didn’t mean”
Exploring Computer Aided Design tools for design ideation

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Abstract:
It is often claimed that Computer Aided Design (CAD) tools are unsuitable for design ideation as they are said to not support serendipitous interpretation, playfulness and creativity. However, this notion is based on anecdotal evidence and research that was done using CAD tools now considered obsolete. This study therefore aims to provide insights on the use of currently available CAD tools for design ideation. This was done by having three experts evaluate the use of pen-and-paper sketches and four different CAD tools for design ideation and discuss the results. The results from this study suggest that CAD tools have the potential to support serendipity and provide an environment for creativity and playfulness. There are several opportunities for the use of CAD tools in design ideation. This is certainly true in design fields where it is notoriously hard to make sketches, such as in lighting design.

Keywords: Creativity, ambiguity, serendipity, happy accidents, re-interpretation

1. Introduction
Sketching is generally thought of as the bread and butter of design ideation. With their ambiguous nature, sketches allow designers to interpret both their own and someone else’s sketch as something different than what was first intended, thereby setting the ideation on a new path. In the literature this is known as re-interpretation (Goldschmidt, 1991) or reflection-in-action (Schön, 1991). Ambiguity is a key benefit for design ideation, as it allows for accidental discoveries of ideas that would not otherwise have occurred. There is a notion that Computer Aided Design (CAD) tools cannot support ambiguity, which has been maintained in studies concluding that CAD tools are only useful for the later stages of the design process (e.g. (Charlesworth, 1998; Stappers & Hennessey, 1999; van Dijk, 1995)). This notion is further reinforced by the tendency to view all CAD tools as a single entity with invariable characteristics (Lee & Yan, 2016). However, this notion originated in studies that are dated and based on CAD tools that are now considered obsolete. As the number of different CAD tools has increased and their usability and capabilities have improved, there is an opportunity to explore if current CAD tools can support design ideation. Since pen-and-paper
sketches are widely used and generally considered the best tool for design ideation, CAD tools for design ideation should retain the strengths of sketches while adding strengths of CAD. Thus we propose that, to determine their use in ideation, existing CAD tools can be evaluated for their ability to 1) retain the strengths of sketches and 2) add the strengths of CAD. To identify these strengths, a literature search was undertaken. Table 1 shows both the strengths and weaknesses of using pen-and-paper sketches and CAD tools.

Table 1. Strengths and weaknesses of using pen-and-paper sketches and CAD tools in ideation

| Strengths of pen-and-paper sketches for ideation | Weaknesses of pen-and-paper sketches for ideation |
|-----------------------------------------------|-----------------------------------------------|
| Allows quick expression (Buxton, 2007; Jonson, 2002; Lim, Qin, Prieto, Wright, & Shackleton, 2004; Wiese, Israel, Meyer, & Bongartz, 2010) | Two-dimensional representation of a three-dimensional object (Sener, Vergeest, & Akar, 2002) |
| Easy to learn and use (Ramimian, Ibrahim, Jaafar, & Fakri, 2008) | |
| Low cost (Buxton, 2007; Gharib, 2013; Jonson, 2002) | |
| Flexible, easy to transform and correct (Goldschmidt, 1991; Jonson, 2002; Ramimian et al., 2008) | |
| Always available (Gharib, 2013; Lim et al., 2004) | |
| Representations do not come across as “finished” (Buxton, 2007) | |
| Supports a co-design process (Gharib, 2013) | |

| Strengths of CAD tools for ideation | Weaknesses of CAD tools for ideation |
|-----------------------------------|-----------------------------------|
| Easy transformation (rotation, scaling, zooming and panning) (Ramimian et al., 2008; Ranscombe & Bissett-Johnson, 2017) | Non-intuitive interface (Kosmadoudi et al., 2013; Ramimian et al., 2008; Sener et al., 2002) |
| Ability to temporally omit an object or group of objects (Ramimian et al., 2008; Ranscombe & Bissett-Johnson, 2017) | Does not support designers habitual activities such as doodling (Bilda & Demirkan, 2003) |
| Automatic undo and redo (Ramimian et al., 2008; Ranscombe & Bissett-Johnson, 2017) | Ideas and thinking are constrained by the capabilities of the tool (Robertson, Walther, & Radcliffe, 2007) |
| Facilitates the creation of shapes that are hard to do manually (Ranscombe & Bissett-Johnson, 2017; Séquin, 2004) | Does not support new ways of viewing the original thoughts (Charlesworth, 1998) |
| Supports visualization of lighting (Andersson, 2017) | |

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2. Expert evaluation

To explore the use of current CAD tools for design ideation and their ability to support serendipitous interpretation, an expert evaluation of pen-and-paper sketches and four different CAD tools was undertaken. The evaluation was done by three experts: a design teacher with 30 years’ experience of design teaching and a background in fine arts (Expert A), a design researcher with an industrial design background and six years of work experience as a design consultant (Expert B) and a 3D visualization teacher with 25 years’ experience in the 3D graphics industry (Expert C). The CAD tools used in the study were SketchUp, Blender, Unreal Engine 4 (UE4) and Autodesk Fusion 360 (Fusion 360). While these tools are not the most used tools in industry, they represent either non-traditional tools, such as UE4 and SketchUp, or forward-thinking versions of traditional tools, such as Blender and Fusion360 and should thus be able to represent the range of capabilities of current CAD tools. Further, the experts were familiar with these tools. Expert A uses all the tools to some extent in his education but is most familiar with pen-and-paper sketching and SketchUp. Expert B is most used to pen-and-paper sketching and tools similar to Blender and Expert C is teaching the use of Blender, UE4 and Fusion 360.

Table 2. Tools used in the study

| Tool         | Type of tool         | Main use                                                   |
|--------------|----------------------|------------------------------------------------------------|
| SketchUp     | Simple 3D modelling  | Simple modelling, architectural visualisation              |
| Blender      | 3D computer graphics | Animation, visual effects, art, digital 3D modelling       |
| Unreal Engine| Game Engine          | Game development, real time visualisation                   |
| Fusion360    | Solid modelling      | Engineering design, solid modelling, simulation, Computer Aided Manufacturing |

The research was conducted in three stages. First, the strength and weaknesses of sketches and CAD tools found in literature were reviewed and expanded upon by the experts. The literature has some spread with regard to design field, time period, and interpretations of what is and is not ideation. Therefore, the views of experts were used to expand and review the list. This revision resulted in 20 beneficial characteristics for design ideation, which were turned into a Likert scale survey. The experts then answered the survey for each of the five tools. Finally, the results were discussed by the experts in two group sessions. As many of the constructs are multi- interpretable and the experts inevitably are more expert on some tools and less on others, group sessions were chosen to enable discussion and ensure that differing views could be debated.

The strengths and weaknesses of sketching and CAD tools found in literature were compiled into a list and sent to the three experts for review. They were instructed to independently add strengths and/or weaknesses that were not present and mark the ones they did not agree with. This generated three new strengths of sketching and three new strengths of CAD tools. Also, one strength of sketching was questioned. In addition, beneficial characteristics were derived from the weaknesses of pen-and-paper sketches and CAD tools and added to the list. These are shown in Table 3. Together, these strengths formed a list of beneficial characteristics for design ideation.
Table 3. Beneficial characteristics derived from weaknesses of pen-and-paper sketches and CAD tools

| Weakness                                                                 | Beneficial characteristic                                      |
|-------------------------------------------------------------------------|---------------------------------------------------------------|
| Two-dimensional representation of a three-dimensional object             | Three-dimensional representation of a three-dimensional object|
| Non-intuitive interface                                                 | Intuitive interface                                           |
| Does not support designers’ habitual activities such as doodling        | Supports designers’ habitual activities such as doodling      |
| Ideas and thinking are constrained by the capabilities of the tool      | Ideas and thinking are unconstrained by the capabilities of the tool |
| Does not support new ways of viewing the original thoughts              | Supports new ways of viewing the original thoughts (i.e. ambiguity) |

The list of beneficial characteristics was turned into a Likert scale survey, where each characteristic was made into a statement. The survey was divided into four sections: Section A: Serendipity and creativity; Section B: Beneficial characteristics derived from weaknesses of pen-and-paper sketches and CAD tools; Section C: Beneficial characteristics based on strengths of pen-and-paper sketches and Section D: Beneficial characteristics based on strengths of CAD tools. Each of the 20 statements was followed by an unmarked, dichotomous scale from Not at all (0%) to Completely (100%) and the experts were instructed to mark on the scale how well they thought the tool fulfilled the statement. The experts independently answered one survey for each of the five tools in the study. Further, they rated their proficiency with each tool on an unmarked scale from beginner (0%) to expert (100%). This was used to make weighed average scores for each tool. After filling out the survey, the experts were gathered for two group sessions to discuss the answers on the survey and CAD tools for ideation in general. The first session was an open and unstructured discussion about CAD tools for ideation as well as the differences between pen-and-paper sketches and CAD tools in design ideation. Preliminary data from the survey was used to guide the session, which lasted approximately two hours. After the data from the survey was finalized, the second session was used to verify some of the answers. It was guided by the final weighed data from the survey. This session lasted 25 minutes. Both sessions were audio recorded and transcribed. The transcription from the first session was analyzed using thematic analysis and the themes are presented in the results.
3. Results

The list of beneficial characteristics and their source (literature, derived from weakness or from expert) is shown in Table 4 below. This is followed by Table 5, which shows the statements used in the Likert scale survey.

Table 4. List of beneficial characteristics for design ideation and their source. The source for respective characteristic is marked with an X in the table.

| Beneficial characteristic for design ideation | Source  |
|---------------------------------------------|---------|
| The tool supports new ways of viewing the original thoughts | X |
| The tool supports creativity | X |
| The tool supports doodling | X |
| The tool has an intuitive interface | X |
| Ideas and thinking are unconstrained by the capabilities of the tool | X |
| The tool supports a three-dimensional representation of a three-dimensional object | X |
| The tool supports ambiguous representations | X |
| The tool supports fast expression | X |
| The tool is easy to learn and use | X |
| The tool is low cost | X |
| The tool is flexible, it is easy to transform and correct the representation | X |
| The tool is almost always available | X |
| The tool supports a co-design process | X |
| The tool supports multiple information types other than illustrations, such as words and material samples | X |
| The tool supports the creation of representation that are not visualizations of the object | X |
| The tool has a low threshold for getting started | X |
| Statement |
|------------|
| The tool supports easy transformation (rotation, scaling, zooming and panning) |
| X |
| The tool supports temporally omitting an object or group of objects |
| X |
| The tool facilitates the creation of shapes that are hard to do by hand |
| X |
| The tool has automatic undo and redo |
| X |
| The tool supports automatic repetition and/or cloning and/or duplication |
| X |
| The tool supports accurate representation of materials |
| X |
| The tool supports Generative design |
| X |
| The tool supports design in a 1:1 scale (VR) |
| X |
| The tool supports visualizations of non-physical concepts such as light and sound |
| X |

Table 5. The statements used in the Likert scale survey

| # | Statement |
|---|------------|
| 1 | The tool supports accidental discovery |
| 2 | The tool supports creativity |
| **Section B** |
| 3 | The tool supports doodling |
| 4 | The tool has an intuitive interface |
| 5 | Ideas and thinking are unconstrained by the capabilities of the Tool |
| **Section C** |
| 6 | The Tool supports quick expression |
| 7 | The Tool is easy to learn and use |
| 8 | The Tool has a low cost |
| 9 | The Tool supports ambiguous representations |
| 10 | The Tool is flexible (It is easy to change or correct the representation) |
| 11 | The Tool is easy to access at any time |
| 12 | The threshold for getting started with the Tool is low |
Representations from the Tool can contain multiple information types other than images (words, numbers etc.)

The Tool supports the creation of representation that are not visualisations of the object, such as mood boards, scenario and layouts etc.

Section D

The Tool supports visualizations of non-physical concepts such as light and sound

The Tool supports transformation of the object (rotation, scaling, zooming and panning)

The Tool supports automatic repetition and/or cloning and/or duplication

The Tool supports temporal omission an object or group of objects (hide/unhide)

The Tool facilitates the creation of shapes that are hard to do manually

The tool supports accurate visualisation of materials

3.1 Survey results

The results from the survey provided some expected and some surprising results. The most interesting results from the survey are presented below.

Section A: Serendipity and creativity

On the first statement, the tool supports accidental discovery, all CAD tools received average scores that indicate that they support serendipitous interpretations to some degree. This was expanded upon in the group discussion and is presented in 4.3 below. Interestingly, Fusion360, a solid modelling tool, received a higher score than both Blender and Unreal Engine. This, the experts thought, was because Fusion360 has successfully integrated the capabilities of several different tools into one software with a flexible interface. However, the experts argued that other solid modelling tools probably would have received lower scores, as they are not as versatile as Fusion360. Pen-and-paper received a weighted average of 98 (out of 100), which is not surprising. The second statement, the tool supports creativity, has similar results, indicating that the CAD tools in this study can support creativity.

Figure 1. Results from the Likert scale statements in section A. The graphs contain the answer from each expert and a weighted average score.
Section B: Beneficial characteristics derived from drawbacks of pen-and-paper sketches and CAD tools.

Statement five, *Ideas and thinking are unconstrained by the capabilities of the Tool*, provides interesting data. Here, pen-and-paper sketches was expected to have a score close to 100, but instead received a score of 70. Moreover, Fusion360 has a score close to as pen-and-paper sketches, which is almost twice as much as the other CAD tools. However, the experts argued that this is very situation dependent. For some problems, such as the human face, tools like SketchUp and Fusion360 will be very limiting. Likewise, sketching will be limiting when designers are faced with problems regarding light.

![Graphs showing weighted average scores](image)

*Figure 2. Results from the Likert scale statements in section B. The graphs contain the answer from each expert and a weighted average score.*

Section C: Beneficial characteristics based on strengths of pen-and-paper sketches

This section is based on the strengths of pen-and-paper sketching. Thus, pen-and-paper sketches are expected to score significantly higher than the CAD tools. However, on statement 7, *the tool is easy to learn and use*, SketchUp received a score almost similar to pen-and-paper sketches. This, the experts thought, was because sketching requires a lot of training to become proficient. However, they agreed that it is easier to teach yourself to use pen-and-paper sketches than CAD tools. Moreover, the experts all agreed that, for a person with no prior knowledge, it would be easier to use pen-and-paper sketches than any of the CAD tools.

On statement 12, *the threshold for getting started with the tool is low*, SketchUp scored highest of the CAD tools. While it is easy to get started with, expert A argued that you quickly reach the limit of what you can do. However, the experts all agreed that the answer to this statement largely depends on who you ask.
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In contrast to statement 12, SketchUp received a significantly lower score than the other CAD tools on statement 9, *the tool supports ambiguous representations*. However, when reflecting on it, expert A thought he might have misinterpreted the statement and that the actual score should have been higher.

Figure 3. Results from the Likert scale statements in section C. The graphs contain the answer from each expert and a weighted average score.
Figure 4. Results from the Likert scale statements in section D. The graphs contain the answer from each expert and a weighted average score.

3.3 Results from group discussion

The results from the group discussion are divided into areas of interest and exemplified with quotes from the discussion. The below quote recounts the design process of a large-scale stage decoration for academic events.

I could have made a physical model, but I made everything in the computer, in 3DStudio [Max]. Sure, I made quite a few sketches on paper, but I soon ended up “sketching” in 3Dstudio where I could see the proportions on the stage and see how they behaved from different views. By changing the shape in one view I could see it repeated several times on the stage. I soon felt that it was not efficient to sketch on paper for this. [Using 3DStudio Max] I could see the results instantly and I could play with the lighting setup. I could probably not have created this, at least not in that amount of time, without 3D graphics software. (Expert A)

As there is a multitude of tools to choose from, the solution space can be explored using many different tools. For some design problems, pen-and-paper sketches can prove difficult to use and CAD tools can, in these cases, be more useful to get the ideation started. Expert A described how SketchUp enables him to experiment with ideas in ways he cannot do with pen-and-paper sketches.
The tools used for ideation also depends on personal preference and skill. As a hands-on example, the experts reflected on what tools they would use to design the partition walls that were placed around the meeting room. Expert A, the design teacher, stated he would use SketchUp because it would allow him to quickly make several versions of the partition walls. Furthermore, he thought that the visualizations in SketchUp have a suitable fidelity level, which do not restrict ideation. As an alternative, he mentioned Fusion360. However, he thought Fusion360 would make it too cumbersome to produce variants. Moreover, he considered the high fidelity of the visualizations in Fusion360 to be restricting. Expert B, who has a background in industrial design, had two different alternatives. If the task was to design the sides of the partition walls, he would use Adobe Photoshop or Adobe Illustrator, photo manipulation and vector graphics respectively, and experiment with materials and pictures. If it was to design the whole partition wall, he would make a physical model or use Rhino3D (3D graphics software). Expert C, the 3D visualization teacher, would have used Blender, Houdini FX (procedural 3D graphics) or UE4. Unreal Engine would allow him to make a model of the whole room and walk around it virtually to experiment with how different heights of the partition walls would affect the meeting area.

[Sketches] are not connected to any shape. You can make everything from faces to words to a forest...a line can be whatever you want. (Expert C)

The experts agreed that sketches are suited for all types of problems, as sketches are not restricted by any shape or problem. Despite which tool is used to ideate, expert A believed that pen-and-paper sketches would be useful. He argued that there are very few who do not sketch at all. Expert B argued that pen-and-paper sketches are used in parallel with other tools; they are used together and complement each other. You can for example draw a corner radius on the paper and experiment with the size until you find the one you feel is right and then do it in the CAD tool.

I have experience of using solid modelling tools in creative and playful ways. (Expert A)

Most solid modelling tools are created for a bottom-up workflow, where designers are supposed to know how they want everything to look. This can discourage experimentation because everything has to be referred to something and it is hard to move objects around. However, expert A claimed he has had experience of using solid modelling as a creative tool. He argued that it is possible to use solid modelling tools for ideation, especially when working alone. Despite this, he reasoned that if tasked to create something using only solid modelling tools, he would probably feel hindered and miss pen-and-paper sketches. Expert B argued that surface modelling tools such as Autodesk Alias and Rhino3D were more useful for creative and explorative work than solid modelling tools.
4. Discussion

The notion that the tool used for ideation depends on individual skills and preferences is interesting as it challenges the necessity of pen-and-paper sketches for design ideation. The experts suggested that there are engineers who are able to use solid modelling tools as an ideation tool in the same way that designers use pen-and-paper sketches. As both the skill, the preference of the designer and the particularities of the design task have influence on the suitability of the tool, there is probably no generic “best” tool. This suggests the need for a designer to be knowledgeable in a variety of tools to be able to efficiently ideate on different kinds of problems.

Some of the beneficial characteristics for ideation were not included in the survey. Automatic undo and redo (Ramimian et al., 2008; Ranscombe & Bissett-Johnson, 2017) was not included, as all CAD-tools in the survey have this, thus making it an uninteresting comparison. Similarly, Three-dimensional representation of a three-dimensional object, which was derived from weaknesses of sketches, was not included as the CAD-tools in this study were all 3D tools. One of the experts suggested Possibility to design in a 1:1 scale, which applies to Virtual Reality (VR). However, as there were no VR tools in the study, it was not included. The strength of sketches to support a collaborative design process (Gharib, 2013) was not included in the survey as this study focused on individual ideation. The strength of sketches that they do not come across as “finished” (Buxton, 2007) was not included, because one of the experts argued that this is not only a benefit but also a weakness. This was based on the argument that while it is beneficial that it looks unfinished, as this generally elicits feedback on the overall idea and not details, the low fidelity of a sketch lacks the authority of a rendering (Jonson, 2002), which is a weakness. Lastly, Generative Design was a strength of CAD tools suggested by one of the experts. This was not included in the survey as this is a topic in itself.

However, the discussion about Generative Design is an interesting take on the future of design ideation. When the generation of potential solutions is done automatically by a computer, it changes the role of designer from creator to decision maker. Thus, instead of generating solutions, the designer would first set the appropriate constraints and then select the most promising solutions. While expert C, the 3D visualization teacher found this very promising, the other two experts were somewhat skeptical. To expert A, the contemplative nature of time-consuming tasks has an inherent value. He argued that when focusing solely on the task, you can access nuances that are not possible to explore in the explosive way of generative design. Expert B also argued that there is a professional pride that would be lost if everyone could use generative design to create objects. He compares to what happened when graphical design was digitalized and anyone could perform tasks that had before required professional knowledge, such as setting a newspaper. Moreover, when the computer generates solutions there will not be any accidents, as it will only respond to the constraints set by the designer. However, in a future with natural language interaction, there is a possibility that the computer misinterprets the constraints the designer sets and creates something that was not intended, thus setting the ideation on a new path by means of “happy accidents”.

There are some limitations to this study. The three experts all work and teach in a CAD dominated environment, which might have affected the results. Adding experts from other design areas such as architecture and textile design would probably have resulted in different and more generalizable results. When evaluating the tools, the experts were not given any input other than the statements to guide their rating. Thus, to improve reliability, a common design problem, e.g. the design of a garden tool, could have been used to frame the evaluation. Moreover, weighted scores were not finalized in time for the first group session, which made this discussion less focused on the survey.
data and more on general reflections. Lastly, digital sketching tools were not included in the study, as this study explored 3D CAD tools. However, it has recently been argued that digital sketching tools are on pair with pen-and-paper sketches in design ideation (Camba, J. D., Kimbrough, M., & Kwon, 2018). The lack of digital sketching tools was also voiced in the group discussions and Expert A argued that they would have scored high in the survey.

5. Conclusions
The aim of this study was to explore the use of currently available CAD tools for design ideation by evaluating their ability to 1) retain the strengths of sketching and 2) add the strengths of CAD. The results from the expert evaluation and subsequent group discussion suggests that the notion that CAD tools are unsuited for design ideation is no longer true. While the results of this study cannot be validated statistically, the rich qualitative data from the discussions together with the quantitative data from the survey both suggest that CAD tools can provide an environment for creativity and playfulness. However, serendipity is the one strength of pen-and-paper sketches that seems most challenging for CAD tools to achieve.

6. Further studies
The results from this study could be used in an experimental setup where designers using different tools, both analogue and CAD, are observed and their use of the beneficial characteristics from this study is identified. This study could also be used to gather data on how well the currently available CAD tools can support serendipity.

One of the experts suggested that a strength of CAD tools is the possibility to design in a 1:1 scale. While the 1:1 scale is only truly accurate in Virtual Reality, it would be interesting to explore how the ability to use 1:1 scale in ideation affects the solution space. For smaller objects this might not change much, but for bigger objects such as cars it could have advantages over traditional methods.

The strength of sketches to support a collaborative design process (Gharib, 2013; Lim et al., 2004) was not included in this study as it was focused on individual ideations. However, it is an interesting topic to explore further, as sketches are most effective when the participants are in the same location. In globalized projects where designers from different locations are involved, sketches can become inadequate (Ibrahim & Pour Rahimian, 2010). In these cases, collaborative VR sketching could be a way to ideate across distances.

Judging by the discussions in the group sessions, the use of generative design in ideation seems to be an interesting but controversial topic. While it is certainly beneficial to generate many solutions, the amount of choices available for the designer when using Generative Design in ideation could prove overwhelming and needs to be addressed. Moreover, the changing role of the designer, from creator to decision maker, is an interesting notion that is worth exploring.
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