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Addressing constraints creatively: how new design software helps solve the dilemma of originality and feasibility

Pierre-Antoine Arrighi, Pascal Le Masson and Benoit Weil

Are designers doomed to sacrifice creativity when integrating new product development processes? Although many studies highlight the need to produce original and innovative designs, maintaining creativity in the design process continues to be difficult due to industrial constraints. Thus, creativity is restricted to phases in the "Fuzzy Front End" to avoid those constraints that might effectively kill it (Amabile, 1998, Reid and De Brentani, 2004). However, constraints are also acknowledged as a resource for creativity, as has previously been shown with artists and engineers (Burkhardt and Lubart, 2010, Sternberg and Lubart, 1999, Le Masson et al., 2011, Goldenberg and Mazursky, 2000). Thus, we pose the following research question: In which cases can a constraint be a resource for creativity? To answer this question, we investigate different types of computer-aided design (CAD) software. Relying on an experimental method, we compare the performance of those types of software at the so-called ideation gap where design sketches are transformed into digital models. We show the following: 1) some CAD software enables designers to work under additional constraints and be more creative and to avoid the tradeoff between robustness and creativity, and 2) understanding this performance means appreciating that such software enables designers to play with the embedded constraints to reveal associated fixations and to design models that follow the constraint but overcome the fixation. Constraints and creativity are linked by two competing processes: constraints decrease the degree of freedom and, as a result, creative possibilities, but embedding constraints increases the awareness of fixations and therefore the capacity to design original models. Today, new CAD tools more effectively support the second process, which leads to "acquired originality" in design.

‘What is not **constrained** is not **creative**.’ Philip Johnson-Laird

Introduction

It is well known that creativity involves not only originality but also feasibility, i.e. not only "good ideas" but also feasible ones. However, creative phases frequently result in conflict with the feasibility constraints of the industrial environment. The challenge for firms is to create a context in which creative people and activities can generate (creative) outcomes while guaranteeing that their work is compatible with and can be assimilated into the industrial design process. Can creative phases be integrated into an industrial design process without damaging or restraining originality? The literature describes different approaches to and advice for combining creativity and industrial constraints in design with respect to issues such as fabrication, costs and the environment. However, there is a continuing debate regarding the best time to integrate and exploit innovative potential during the new product development (NPD) process.

For some researchers, creativity must be fostered at the beginning of the design process. This approach, first popularized by scientists working primarily in automobile design (Fujimoto, 1997, Thomke and Fujimoto, 2000), is now proposed by publications that take the "Fuzzy Front End" approach to NPD (Khurana and Rosenthal, 1998, Reid and De Brentani, 2004). Following the hypothesis that conforming a design to industrial constraints impedes creativity, the Fuzzy Front End approach advocates for increasing the creative potential before addressing constraints. In this scheme, the best guarantee for high levels of creativity appears to be maximum freedom at the beginning of the design process (Karniel and Reich, 2011). The NPD process then consumes this initial creativity potential. Under this approach, there is a tension between creativity (which is considered as a number of degrees of freedom) and constraints (which reduce the degrees of freedom and should be introduced later in the process). Thus, there is a trend in the creativity and innovation management literature to posit an opposition between creativity and constraint, i.e., between originality and robustness.

A different community introduces the design process as a succession of iterative steps that *all* require the creative capacity to challenge previous choices and to continuously "reframe the problem" with creativity. Donald Schön (Schön, 1983, Schön, 1990) was one of the first to consider design to be more than a problem-solving activity in that managing constraints during the design process should be coupled with creativity and originality. Constraints can trigger innovation and lead to original and creative design. This concept is understood by artists (writers, poets, painters, etc.) who use constraints to increase their creativity, such as the French literary movement known as "Oulipo" ("Ouvroir de littérature potentielle", which is roughly translated as the "workshop of potential literature"), in which creativity is stimulated by writing constraints (e.g., using particular words, avoiding certain letters, etc.). This concept might also apply to engineering design. It has been shown that recent design theories tend to support the dual improvement in robustness and generativeness, which leads to interweaving these terms in design processes (Le Masson et al., 2011).

Thus, there is a research gap in the creativity and innovation literature: are these two types of performances—generativeness and robustness—necessarily evolving in opposite directions during NPD, or is it possible for them to grow simultaneously during NPD? If the latter is true, can we identify some of the conditions for creatively addressing constraints to solve the dilemma between generativeness and robustness?

To bridge this complex research gap, we focus specifically on computer-aided design (CAD) software tools. CAD tools are the dominant means of production in the design field, and examining their use can yield vivid evidence regarding the design process. Today, CAD tools confront the tension between originality and feasibility when engaging with the so-called "design gap" (Wendrich et al., 2009), i.e., the loss of originality that accompanies coding design sketches into digital models in CAD suites. We compare the capacities of two different generations of CAD tools in terms of generativeness and robustness (i.e., increase or loss of originality and increase or loss of feasibility). Both tools, which belong to the same software design suite, are used to generate numerical models. The first CAD tool tends to apply as few constraints as possible to the shape design process to correspond as faithfully as possible to the initial sketch. Shapes are generated through process operations (e.g., blueprints, extrusions, etc.). A second CAD tool immediately embeds certain constraints (on optical quality) on the shape and relies on a new shape deformation process, which is closer to the paradigm of clay deformation. Thus, the two tools

differ in how they address constraints. After the shapes are generated, we assess the respective effects that using each of these two tools has on the robustness and generativeness of concepts during this design step.

We first present the theoretical background underlying our research hypotheses. We then detail our experimental plan with a presentation of our experimental logic, the variables and the measures that we used in the experiment. This introduction is followed by sections that present the analysis of the tools' performances, discuss our results and offer our conclusions.

Motivations, Theoretical Background and Hypothesis

Many studies have shown that creativity and originality are important to triggering, fostering and sustaining innovation (Olson et al., 1998, Verganti, 2008). However, creativity and innovation capacities are difficult to integrate into industrial environments. The challenge for firms is to support originality and “outside-the-box” thinking while guaranteeing that such creative work is compatible with and can be assimilated into the industrial design process. Can this apparently direct trade-off between creativity and constraint be resolved? *That is, can creative activities be integrated into an industrial design process without damaging or restraining the objective of obtaining original output?*

A divided literature regarding management of creativity and industrial constraints

Certain researchers have found that it is necessary to foster creativity at the beginning of the design process. This approach was first popularized by scientists working primarily in the field of automobile design (Midler, 1995) (Fujimoto, 2007).

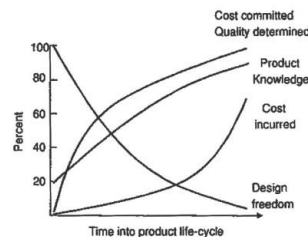


Figure 1. Product knowledge and design freedom versus time (Karniel & Reich, 2011)

Karniel and Reich (Karniel and Reich, 2011) advocate for this approach, based on the work of Ullman (Ullman, 1997). When creating a new design, there is a progressive trade-off between the degree of freedom in a project (which is also constrained by the remaining possibilities of action) and designers' knowledge regarding the project. The degree of freedom is directly linked to various means of exploration (also called possibilities) that have been preserved to enable innovation and that can be used to resolve the issues encountered. This freedom is consumed like capital as the design process progresses. This type of analytical approach is highlighted in publications that emphasize the Fuzzy Front End approach to NPD (Khurana and Rosenthal, 1998). A Fuzzy Front End approach also requires a phase of maximum creativity at the beginning of the design process that should be free from constraints to enable consideration of the widest range of solutions possible, according to Reid and de Brentani (Reid and De Brentani, 2004). These recommendations are intended to promote the ultimate convergence toward a

successful design because all the unpredicted future issues can be anticipated by preserving the maximum degree of initial freedom. Creativity is consumed during the early phases; as options become progressively out of reach, freedom decreases. Thus, there is a tension between the freedom of creativity and the constraints of practical development.

Other scholars consider the design process as a succession of iterative steps, in which each step requires the capacity to challenge previous choices and to continuously and creatively “reframe the problem”. In Van de Ven’s “Innovation Journey” (Van de Ven et al., 1999), intensive and radical innovation is achieved by means of a succession of iterative (and sometimes creative) steps. In other words, creativity is not always accomplished at the beginning of the innovation journey. Donald Schön (Schön, 1983, Schön, 1990), who was one of the first to consider design as more than a problem-solving activity, considers the design issue to consist of ‘framing’ and reframing a problem, and creative framing is constructed from the materials of problem situations. Schön also posits that each move is a local experiment that contributes to a global experiment in reframing the problem. Under this framework, managing constraints during the process is coupled with creativity and originality. This approach is widespread in many research communities and recommends including creative phases throughout the design process (Couger, 1990, Dorst and Cross, 2001). Buijs (Buijs, 2003) uses the expression “circular chaos,” rather than “linear logic,” to refer to the design process. Some authors stress that a shift in a creative concept can occur even late in the design process (Seidel, 2007). Certain methods, such as TRIZ (sometimes defined as the “theory of inventive problem solving”), are supposed to creatively address constraints (Moehrle, 2010), whereas some tools, such as CAD software, enable the exploration of alternatives and preserve room for innovation throughout the design process (Thomke and Fujimoto, 2000). Thus, there can be a form of complementarity between constraints and creativity.

Deciphering from a design theories perspective

To understand why there are such contradictory propositions, it is important to clarify the analytical framework. On the one hand, the tension between creativity and constraint arises out of an analysis of the development process as a problem-solving issue. In a problem-solving framework, constraints indicate less freedom and creativity and are directly linked to the degrees of freedom, which means that there is an inherent conflict between creativity and constraints. On the other hand, it has long been shown that problem solving takes a view of design processes that is too limited (Schön, 1990, Rittel, 1972, Hatchuel, 2002). For example, from the broader perspective of design theory, a design process can consist of “reframing the problem” or, more generally, of generating original products and services that embody newly invented performance criteria. This concept describes the logic of originality in creative design: the outcome is not a “solution” to a problem but is original precisely because it cannot be deduced from a given set of rules (Boden, 1990). Contemporary design theories compete to model a growing number of generative processes, i.e., outside-the-box processes that extend beyond problem solving. In general terms (see the synthesis in (Hatchuel et al., 2011)), all these processes can be characterized by their capacity to generate design propositions from a given knowledge set, which is a process that can be characterized by two criteria:

- i) *generativeness*, i.e., the ability to produce design proposals that differ from existing solutions and design standards; and
- ii) *robustness*, i.e., the ability to produce designs that meet constraints (such as functional requirements, feasibility, production constraints, legal constraints, etc.).

Together, these theories form a consistent body of knowledge that aims to enhance the generativeness of a design *without losing its robustness*. This approach can be called a “simultaneous solution” of the two criteria. Well-known design theories—including General Design Theory (Yoshikawa, 1981), Axiomatic Design (Suh, 1990) and Concept-Knowledge (Hatchuel and Weil, 2009)—recommend that practitioners take these two dimensions into account and manage them simultaneously throughout the entire design process to develop products that are both original and feasible (i.e., that function under the applicable constraints). Therefore, there can be a positive relationship between robustness and originality, at least in theory.

Thus, within the framework of design theory, there are actually two competing phenomena:

- On the one hand, if they are accepted and met in the final output, constraints will continue to lower degrees of freedom, such as in problem solving.
- On the other hand, constraints can increase originality by leading to design outcomes that differ from existing solutions.

These two phenomena are present in design processes, and their balance might explain why some design processes take the form of a tradeoff between generativeness and robustness, whereas other processes appear to creatively address constraints and simultaneously increase generativeness and robustness.

Therefore, there is a research gap: can we identify those critical features of design processes through which constraints might lead simultaneously to more generativeness and more robustness?

The strong tropism of design tools and hypothesis formulation

We do not study every feature of the entire NPD process in this study. Instead, we focus on one specific aspect: software used to support NPD and, more precisely, software used at the design gap. This focus helps us formulate more specific research questions and leads us to use a relevant methodology. Let us first briefly review design tools and how they contribute to the generativeness and robustness of the design process in which they are used.

Tools providing high generativeness and poor robustness

The first category of tools offers a high capacity for conceptual exploration—at little or no cost—but is not integrated into the industrial process, which can result in the loss of design intentions during the production process. These tools are based on sketching and tend to share most of the properties inherent in sketching: they are quick, timely and inexpensive. Sketching itself is obviously one of these tools, but we can also consider clay modeling and patchworking as belonging to this category because they are characterized by certain properties and uses during the early phases of the design process. These tools aim to provide maximum creativity to their users and are frequently used to present a set of possibilities at the beginning of a design process (Christiansen et al., 2010). These tools are also well suited for introducing rapidly formalized concepts and are considered an explorative method, which makes them consistent with the generativeness of the design process. Sketching makes mental models easy to represent and manipulate, and its simplicity aids designers in reinterpretations and discussions with others (Van Der Lugt, 2002); moreover, sketching can be used as a communication tool for conveying an industrial designer’s ideas or concepts to other designers, engineers or managers, as noted by (Perks et al., 2005).

In addition to traditional “sketching” tools, digital design interfaces that mimic such traditional tools have appeared (Bae et al., 2008) that have the same advantages as traditional tools, such as good support for creativity (Barone, 2004), but that also share the flaws of traditional tools. These “digital sketching” tools provide poor integration, primarily because 3D models are not compatible with CAD industrial

environments, and they contribute little to a design's robustness. These tools are not assessed in this paper because they do not qualify as integrated. *Thus, in this category of tools, robustness is traded for maximum generativeness.*

Tools providing high robustness and poor generativeness

As numerous industrial tools were progressively introduced into design environments, the first generation of CAD tools gave creative professionals such as industrial designers (IDs) the opportunity to use the same means of operation as engineers. However, although these tools provide good integration, they have the unwanted tendency to sacrifice creativity by restraining the possibilities of conceptual exploration. This category of tools tends to bind creativity and overlies upon original concepts by integrating them early in the process through technical and even legal constraints.

These limitations result because these tools were first designed *for engineers* (Henderson, 1998), and their first intended use was to increase the quality and robustness of designs by limiting the most costly iterations in different media (such as blueprints, prototypes and 3D models). Like sketches, the first generation of CAD tools proved to be very good coordination and collaborative tools that had the advantage of providing unambiguous product representations (Thomke, 2003). These tools could generate "boundary-objects" and had good capabilities for transferring, translating and transforming knowledge across syntactic, semantic and pragmatic boundaries (Carlile, 2002, Carlile, 2004) among both IDs and other design participants (e.g., managers, engineers, marketers, etc.). However, along with these qualities, the first-generation CAD tools had several drawbacks that limited creativity: limitations on modeling possibilities that led to circumscribed thinking, premature fixation that required detailed modeling too early in the process and bounded ideation (Robertson et al., 2007). IDs also complained about the lack of control and spontaneity with these tools and felt that their intuitive design qualities were transformed into virtual data processing (Wendrich et al., 2009). Computers compartmentalize, break activities into isolated steps and focus on rigid logic and literal meanings (Diffrient, 1994); when using these tools, IDs also tended to focus on geometrical aspects and neglect meaning creation (Verganti, 2008), one of their essential competencies. Thus, this type of tool trades generativeness for maximum robustness.

The first generation of digital tools thus restricted creative designers' choices: on the one hand, there were creative tools, such as sketching, that were not well-suited to industrial requirements because they traded robustness for generativeness. On the other hand, effective integrative tools for managing collaboration and industrial constraints bounded (or obliterated) ideation and thus effectively traded generativeness for robustness. This literature review of IDs' design tools seems to indicate a strong split related to the tradeoff between robustness and generativeness.

Hypothesis formulation

To confirm the properties of the first generation of CAD tools with respect to design tradeoffs, we formulate our first working hypothesis.

- **H1:** When designers use first-generation CAD tools, they can improve the **robustness** of concepts, but at the expense of **generativeness**.

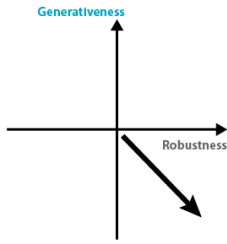


Figure 2. H1 mapped in the robustness/generativeness space

In this context, it was difficult to find tools that can simultaneously address robustness and generativeness. Today, however, a new generation of digital tools has integrated itself into product design software suites (and are effective regarding robustness, as were the first-generation CAD tools) that claim to maintain designers' abilities to naturally shape objects by following the logic of clay modeling or sketching in a virtual environment. This new generation of tools tends to increase robustness *and* generativeness, as some of its users claim. To assess the capacity of the new generation of CAD tools to simultaneously increase robustness *and* generativeness, we formulate our next working hypothesis.

- **H2:** When designers use newer generations of CAD tools, they are able to simultaneously **improve** the **robustness** and **generativeness** of concepts.

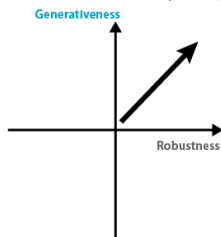


Figure 3. H2 mapped in the robustness/generativeness space

This result is the first step in showing that there is not necessarily a conflict between constraints (represented by an increase in robustness) and creativity (represented by an increase in generativeness). If H2 is confirmed, we study the new-generation CAD tools to understand how software assists in creatively addressing constraints. In particular, we aim to discover whether there is a detailed causal relationship between an increase in constraints (i.e., an increase in robustness) and an increase in generativeness. In addition, we also attempt to discover the phenomenon that helps us use constraints in a generative way. Thus, our third hypothesis is as follows:

- **H3:** The new generation of CAD tools accounts for more constraints and helps designers to creatively address those constraints.

Experimental method

To test our hypotheses, we rely on an experimental method. Below, we present the experimental protocol (task, sample, observations, etc.).

Choice of design step and tools

The basic idea of the experiment consists of measuring how two different CAD tools lead to two different types of performance in terms of generativeness and robustness.

The design task. We focus on one specific task in the entire development process: the so-called ideation gap (or design gap). This phase is one of the most emblematic in the design process, namely, the transition between “traditional” and “numerical” media (Wendrich et al., 2009). At this brutal and stringent transition point, the task consists of taking concepts represented using traditional means (sketches, mock-ups, prototypes) and modeling (digitizing) them on computers. This step is stressful for the software and exposes both its limitations and capabilities. This transition is critical because there is a risk of losing the initial design intentions during the switch from traditional to digital media. The integration of concepts into the software design suite is intended to support the subsequent development of the design into the final product. Thus, after the design gap, robustness should be increased and industrial constraints should be addressed, but the greatest threat is that these objectives will be achieved at the expense of a loss in generativeness.

We compare two software packages used by designers on a daily basis to bridge the design gap. Both packages integrate handmade sketches into the same software design suite and seek to satisfy certain modeling constraints. Each design tool is a so-called “workshop” that helps the designer transform a handmade sketch into a digital shape, as illustrated in Figures 5 and 6.

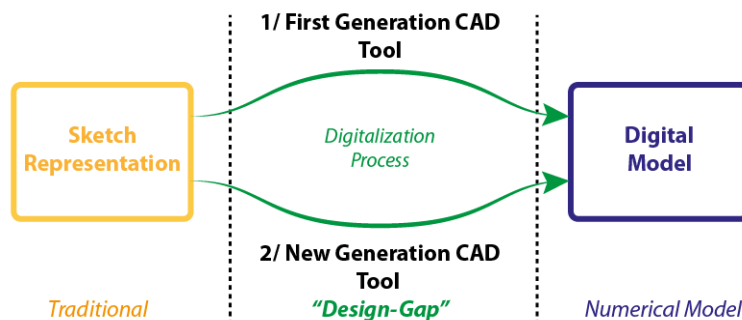


Figure 4. Managing the design gap with two different digital tools

The first workshop that we tested is an archetypal first-generation CAD tool. This tool uses procedural commands, and modeling appears as a succession of steps in which blueprint construction (called two-dimensional (2D) sketches in the software) is followed by employing parameterizable functions (such as extrusions, revolutions or sweeps) in iterations. The tool is capable of producing very high quality surfaces (up to a Class A standard, which is the highest in the industry).

The new-generation CAD tools provide integration within the same design suite. The global design suite is suitable for any type of industrial design and is composed of specialized workshops (i.e., other design tools for specific tasks). The models generated within the suite are fully compatible with various workshops. Any creative design performed with either tool can then be transmitted to other designers and has the capacity to integrate industrial constraints.

Design briefs used in the experiment

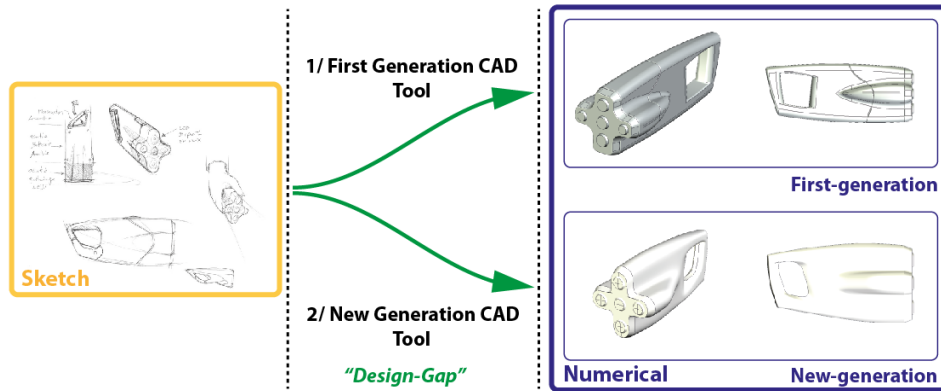


Figure 5. Materials collected before and after the design gap

IDs in most companies typically cross the design gap with first-generation CAD tools because they serve as direct entry points into the industrial world and its CAD codifications and specifications, which are required for subsequent manufacturing processes. Our goal is to assess the capabilities of recently introduced new-generation tools and to compare them with their predecessors to determine whether these new tools can verify H2.

Sample: For the experiment, we worked with six IDs from a well-known CAD company. All the participants had ID educations and had worked as designers for three to 20 years using these two types of tools. These users had experimented with the tools. In this way, we avoid a bias linked to experience with the tools and in-experiment learning processes.

The IDs were given design briefs that described precisely what was expected of them.

- In the first step, the IDs were asked to produce two different concepts of an “autonomous portable lamp” and to represent them with sketches. Each of the IDs was given full access to ideation materials: pen, paper, pencils, erasers and a computer with graphing software. They had one hour to complete their designs and were free to ask questions. When they were finished, their sketches were collected and scanned.

- Next, the IDs were asked to make 3D models of their sketched concepts with both the first- and new-generation CAD modeling tools. They had one hour for each concept model, i.e., a total of two hours. The IDs actions were recorded throughout the experiment. To avoid any learning effects, we randomized the modeling: half of the IDs began with the first-generation software, and the other half began with the new-generation software.

Data and evaluation protocol

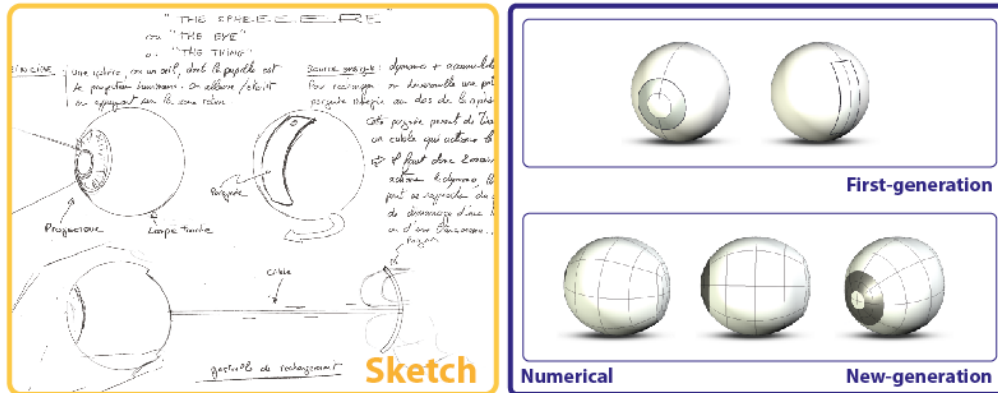


Figure 6. Example of a sketch (before the design gap) and CAD representations (after the design gap; with first-generation CAD tool (first line) and second-generation CAD tool (second line) (representations collected for Concept 4)

For each sketched concept, we obtained two sampled numerical representations, which resulted in 24 representations. Figure 7 shows a collection of sketches and 3D models for one concept.

For an assessment of their respective contributions to design robustness and generativeness in the design gap, originality and feasibility items were scored according to the literature (Runco and Charles, 1993, Magnusson, 2003). The formal originality of a concept is consistent with the generativeness of a design. A highly original shape is a guarantee of high creative potential, which is available for exploration and innovation throughout the design process. This originality of design is uncommon and surprising and can reveal new meanings. The formal feasibility of a concept is similar to the robustness of a design, i.e., its acceptability during the remainder of the design process. A feasible shape enables a simplified design with fewer unknowns and difficulties; in particular, it has a given quality of surface, which can be rated and evaluated using mathematical and optical criteria. When interviewing evaluation experts after the experiment, they confirmed that they considered a design to be robust when it met the constraints listed above (a digital shape that can be handled by CAD software suites—throughout the remainder of the development process—and that meets “quality” criteria, i.e., it is (likely) to be feasible and simple, and more precisely, to avoid any optical or other types of defects). The evaluation experts also confirmed that they considered a shape to be “original” when it was different from what they expected but that also seemed to be iconic, exact and simple.

We provide a graphical example of what is called surface quality. Along with visual criteria, it is also possible to describe the quality of a shape in mathematical terms (see Figure 8).

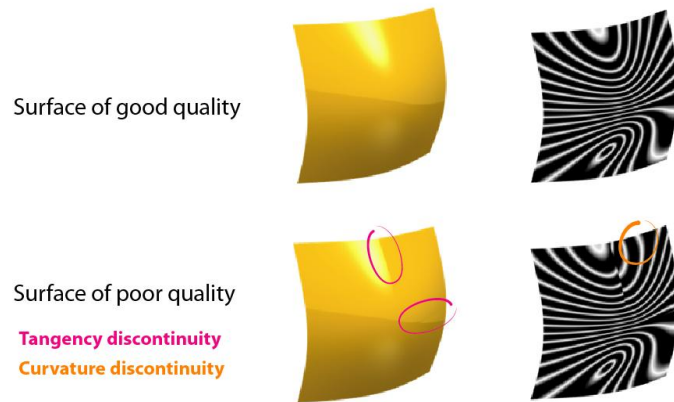


Figure 7. Evaluation of surface quality

To evaluate the evolution of feasibility and originality during the design gap, we used an expert evaluation, the “Consensual Assessment Technique” (CAT), developed by Amabile et al. (Amabile, 1996). We selected five different IDs who were experienced in assessing design concepts and worked as managers. These IDs were used to rapidly evaluate projects under development; in the remainder of this article, these IDs are referred to as “experts”. To enable these experts to evaluate the evolution of feasibility and originality, we provided them with the reference sketch and the pair of digital 3D models for each concept. The experts rated the progression of feasibility and originality of the concept’s shape from the sketch to the digital model using a Likert scale (Likert, 1932) of five items: strong decrease (-2), decrease (-1), neutral (0), increase (+1) and strong increase (+2). The experts conducted this process twice, once for the first-generation CAD tool model and again for the new-generation CAD tool model.

Ultimately, we obtained two evolution grades for each concept and for each type of modeling tool, i.e., one for feasibility evolution and the other for originality evolution. With 12 concepts and 24 numerical models, the experiment yielded 48 evolution grades.

To assess the respective impact of each CAD tool on concept feasibility and originality, we calculated the progression for each modeled concept property as the mean of all five experts' scores. The result is an aggregated Δ Originality (ΔO) and a Δ Feasibility (ΔF) for each numerical concept that is matched with the tool used. This result can be mapped on the ΔF - ΔO space and provides a design gap performance measure for a single concept, depending on the tool used.

Results

Quantitative results (H1 and H2)

As described above, we characterized the design gap performance of the tools and mapped it in the ΔO – ΔF space. When the experts rated a strict progression of originality and feasibility ($\Delta O < 0$ and $\Delta F > 0$), the concept had become simultaneously more original and feasible after the design gap. We call this result a simultaneous solution. With reduced originality and increased feasibility ($\Delta O \leq 0$ and $\Delta F \geq 0$), the concept gains feasibility, but at the expense of its initial originality. We call this result a trade-off. In other configurations, there is a strict decrease in feasibility ($\Delta F < 0$), which might indicate a gain (“Other1”) or a

loss (“Other2”) in originality. The results of the evaluations of the progressions are illustrated in Figure 10 for each tool.

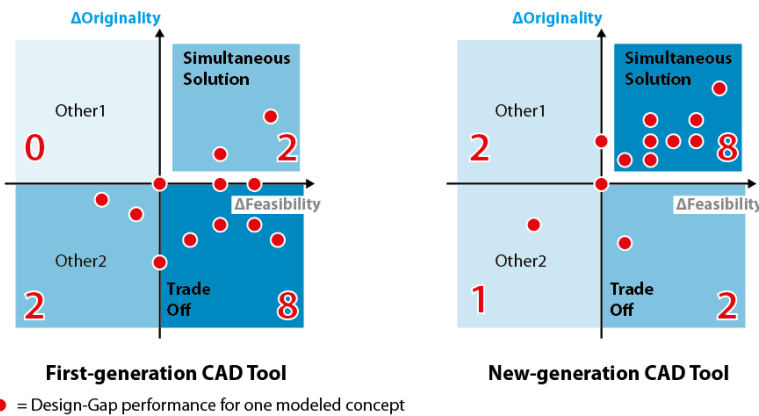


Figure 8. Map of the design gap performance of first- and new-generation CAD tools

The results are visually eloquent, but we now test our hypotheses statistically.

H1-0 hypothesizes that the design gap performance of the first-generation CAD tool leads to a uniform distribution among the four different sectors: trade-off, simultaneous solution, “Other1” and “Other2.” We test H1-0 with a χ^2 test for a two-sided 2.5% trust interval. We obtain a total distance of 12 for the χ^2 , which is superior to the table distance of 9.3. Thus, we reject H1-0 and formulate a *non-uniform* distribution of design gap performance for first-generation CAD tools. We next test whether there is a significant difference among the proportions of tradeoff, simultaneous solution, “Other1” and “Other2.” A difference is evident in tradeoff occurrences, as can be observed by examining the two-sided 5% confidence interval: with 8 of the 12 concepts, the frequency of tradeoff is $66.7\% \pm 22.3\%$, whereas for simultaneous solution, the frequency is $13.7\% \pm 17.6\%$. Thus, tradeoff frequency is significantly superior to simultaneous solution frequency (and “Other1” and “Other2”). Therefore, we conclude the following for **H1: when IDs use first-generation CAD tools, they improve the formal feasibility of concepts at the expense of formal originality.**

H2-0 hypothesizes that the design-gap performance of the new-generation CAD tool leads to a uniform distribution among the four different sectors: trade-off, simultaneous solution, “Other1” and “Other2.” We test H2-0 with a χ^2 test for a two-sided 2.5% confidence interval. We obtain a total distance of 11.3 for the χ^2 , which is superior to the table distance of 9.3. Thus, we reject H2-0 and formulate a *non-uniform* distribution of design gap performance for the new-generation CAD tool. We next test whether there is a significant difference among the proportions of tradeoff, simultaneous solution, “Other1” and “Other2.” A difference is evident in simultaneous solution occurrences, as is shown in the two-sided 5% confidence interval: with 8 of the 12 concepts, the frequency of simultaneous solution is $66.7\% \pm 22.3\%$. For tradeoff, the frequency is $13.7\% \pm 17.6\%$. Thus, the simultaneous solution frequency is significantly superior to the tradeoff frequency (and “Other1” and “Other2”). Therefore, with respect to **H2**, we conclude as follows: **when IDs use the new-generation CAD tool, they can simultaneously improve concepts’ formal feasibility and originality.**

Qualitative results (H3)

Now that we have shown an (unexpected) relationship between robustness (constraints) and generativeness (creativity), we analyze these phenomena in more depth. In particular, we underline, in the theoretical framework, that a design theory perspective reveals the existence of two competing processes when a designer addresses constraints: on the one hand, constraints lower degrees of freedom, tending to decrease the capacity for originality and generativeness; on the other hand, constraints can push a designer to design an unexpected outcome, which could indicate that a constraint might increase generativeness. In our experimental study, how do these two processes unfold? We clarified this unfolding by means of an in-depth study of the use of CAD tools by designers and complementary interviews with users.

- 1- Studying the software in more detail, it appears that both software suites help meet the CAD-compatibility constraint: any shape coded with either software suite can be coded in CAD to be used in the rest of the CAD suite. The second generation integrates an additional constraint: the software permits any shape created by the user to meet the optical quality criteria. This result derives from the software principle: in the second-generation software, an initial simple rough shape is provided, and the user deforms it step by step into a new shape. The initial shape meets the relevant optical quality, and every transformation is coded such that the resulting shape also follows the optical quality criteria (this results because the surface always follows a certain curvature continuity). *Thus, the first-generation software tends to embody fewer constraints than the second-generation software.*
- 2- This property of the second-generation software has an immediate consequence: with the second-generation software, is it *impossible* to design a shape that would not follow the optical criteria. Thus, there is a restriction in the degree of freedom left to the users. All the users and software designers confirmed this property: every shape that can be created with the second-generation software can be made with the first-generation software, whereas some shapes that can be made with the first-generation software cannot be made with the second-generation software. There are clearly fewer degrees of freedom in the second-generation software. Thus, the experiment follows the first process: *more constraints lead to fewer degrees of freedom.*
- 3- Conversely, the users also explain that manipulation of the modeled objects in the second-generation software is direct and provides instant feedback via a “manipulation box.” This process allows for a high degree of precision in creating and modifying shapes. Software users can work on shapes with substantial control and speed without invoking commands, functions or parameters. Notably, users sometimes refer to this tool as a type of clay modeler. Thus, they are able to visualize many shapes that follow the constraints. Furthermore, in this process, they are able to consider the “usual” shapes that could be obtained following the constraints and to explore whether there were “unusual” shapes that follow the constraints but diverge from expected shapes. Here, we understand how the second (competing) process occurs: by enabling users to play with constraints, the software helps visualize “expected” shapes and helps the user to design an unexpected shape to meet the criteria. *Embedding the constraints diminishes the degree of freedom but can help users to depart from the “expected” shapes.*

Thus, this study confirms hypothesis H3: The new generation of CAD tools takes more constraints into account and help designers creatively address those constraints.

With the second-generation software, quality constraints trigger creativity. This finding may appear surprising at first, but the literature on multiple domains is characterized by many examples of creativity increased by constraints, as brilliantly illustrated by G. K. Chesterton: “Art consists of limitation. The

most beautiful part of every picture is the frame.” What we add to this illustration is that the tool itself (not only the designer) embodies the constraint. The software tools that help the designer to simultaneously increase robustness and originality are actually engines that help the designer play with constraints in a generative way - these engines enable the designer to creatively address constraints.

This result has an interesting consequence: the originality of the final shape is deeply linked to the validated optical criteria. Thus, one can consider that the originality is validated as well. The two dimensions, feasibility and originality, are now coupled together in a positive manner: if maintaining the optical quality is an objective, then the shape and the originality associated with it must be preserved. Conversely, reducing shape originality does not increase robustness but instead decreases the optical quality and decreases robustness. Freezing the degree of freedom of a shape increases robustness and increases originality. Thus, one can speak of “robust originality” or “acquired originality.”

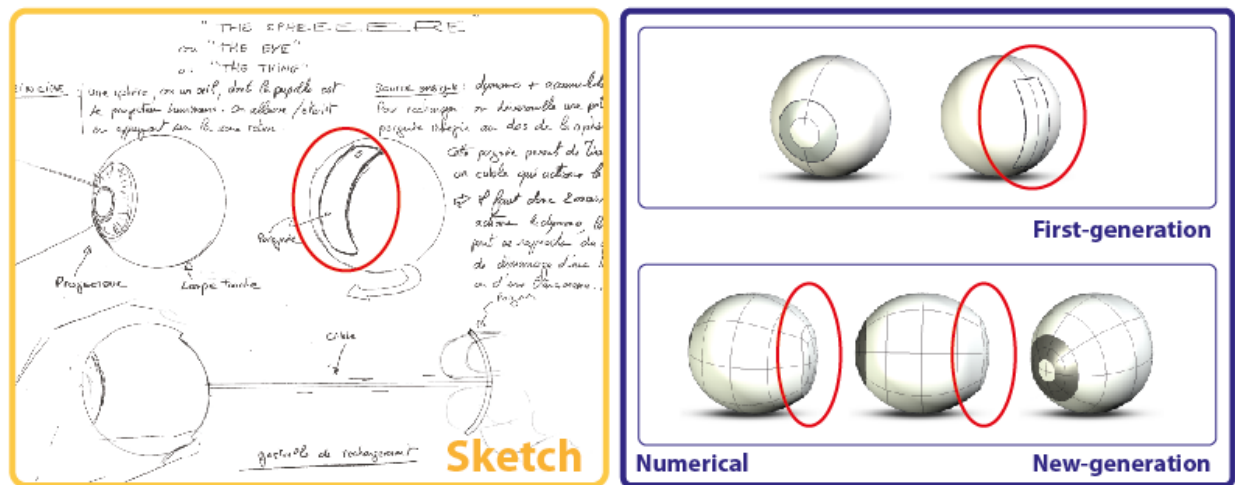


Figure 9. Appearance of a new shape attribute using the new-generation CAD tool

This concept is illustrated above (see Figure 10): the first generation software transforms the initial sketch into an ovoid shape. The ovoid surface actually corresponds to what is typically expected to follow the optical quality criteria (the evaluation is as follows: “less originality, more robustness”). With the second-generation software, the final shape is evaluated as having “more originality and more robustness”. The experts justify their evaluations by explaining that a facet appears on the ovoid shape. Because that shape is coded by the second-generation software, the user is sure that it will meet the optical quality criteria. However, the shape is more surprising and original than the almost perfectly spherical model. The designer can alter the spherical design while maintaining optical quality, adding a facet that was barely present in the original sketch and that is not typically associated with A-level optical quality (A-level optical quality favors strong surface continuities, whereas facets tend to introduce discontinuities). The constraint led to originality, and the originality was acquired jointly with robustness.

Discussion and Further Research

Limitations

Due to the exploratory nature of this experiment, our findings have certain limitations. The first restriction concerns the limited number of representations, concepts and IDs used in the experiment. This limitation may have seriously misleading effects, although our results seem to indicate a global trend that supports our findings. The design of the experiment (a comparative empirical study that resulted in paired samples) helped achieve a high confidence level despite its small sample size. The shape originality and feasibility offered by the modeling tools might be correlated with the type of concept, which in our case was an “autonomous portable lamp.” It would be useful to conduct our experiment with several concepts depicting various products from different industries.

Side Findings and Further Developments

Sketching is not the only representation that IDs use for concept exploration. They also frequently manipulate clay models, 3D digital models made with “3D artist”-type tools, prototypes and even photomontages. It would be useful to measure the progression of shape originality and feasibility when transitioning from those types of media to 3D industrial models.

In future work, we propose varying experts’ evaluation methods by providing them with efficient 3D viewers prototyped to enable a different perception of numerical models. We also note that the time taken by the designers to model the different representations of their concept was correlated strongly with the tools that they used. First-generation CAD tool modeling took approximately 40% longer than modeling with the new-generation CAD tool. In addition to these tools’ respective contributions to product design, it would be interesting to assess their productivity. We also plan to obtain a deeper understanding of acquired originality and to attempt to model it, along with how it might be obtained in different contexts.

Conclusions and Managerial Implications

Conclusions

The results of this experiment include several new findings and confirm certain results in the literature. The dominant industrial tools, i.e., software similar to the first-generation CAD tool used in this experiment, have a powerful capacity to dramatically improve the robustness of a design, but at the expense of its generativeness. By contrast, the new-generation CAD tool provides the means to increase robustness and generativeness. Moreover, we have shown that this property arises because the tool is an engine that can be used to explore a variety of ways to address constraints and to depart from the “usual” shapes, which thus increases originality while meeting constraints.

Managerial Implications

With procedures such as those in the new-generation CAD tools and their capacity to simultaneously enhance generativeness and robustness during design processes, designers may be able to manage the generativeness and robustness of their designs to best fit the needs of their companies at any given moment. With such capabilities, the design process could be revised, and its versatility and robustness could be improved markedly, as illustrated in Figure 11.

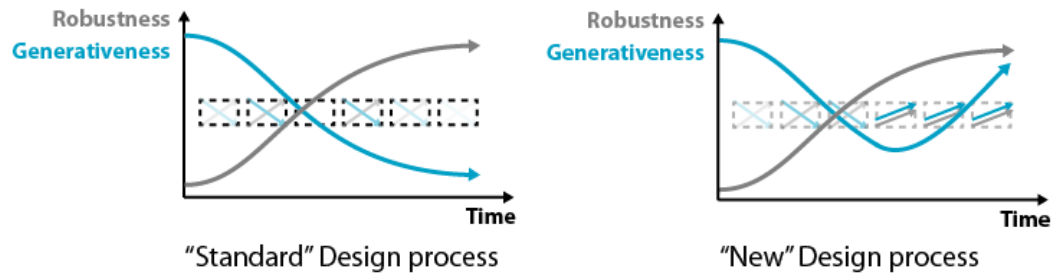


Figure 10. "Standard" and "New" design process profiles

With such a tool, it is not necessary to begin with a high originality level. It is possible to increase generativeness even when robustness must be increased. This experiment also suggests that because tools are now able to simultaneously enhance a concept's robustness and generativeness, a new design process can be imagined and applied in industry. This process would have properties other than tradeoffs and offer designers the capacity to add robustness and/or generativeness as required. Thus, the new design tools' ability to creatively address constraints paves the way for new innovation and creativity management processes.

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