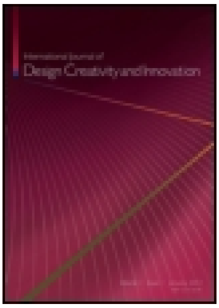

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# A descriptive framework of the design process from a dual cognitive-engineering perspective

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# A descriptive framework of the design process from a dual cognitive-engineering perspective

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This article proposes a new descriptive framework, which we label as the "ideation framework" (IF), of the design process from a dual cognitive-engineering perspective, partly based on existing frameworks from both fields and previous work by the author. The framework is for the ideation or front-end phase of the product development process, representing the interface between cognitive psychology and engineering design. Three domains – inspiration, decomposition, and integration – and three spaces – problem-space, idea-space, and concept-space – are the elements of the framework. The iterative flow of the engineering design process passes through the three domains in a semi-controlled way, through a sequence of specialization and generalization process loops in and between the spaces. An empirical descriptive examination of the ideation process is performed using designers with limited design experience. The designers were faced with a design problem that they had to solve in a limited period of time. Their designs were analyzed, and a post-exercise interview was done to uncover each of the participants' design process. The empirical work indicates these designers worked in a manner largely consistent with the IF.

**Keywords:** creativity; engineering design; descriptive framework; novice designers

## 1. Introduction

The clarification of how the mind works is an issue of great significance for all the disciplines involved in the study of the mind in which one can include cognitive psychology (Thagard, 2005). It is possible to say that we are beginning to understand how design processes are undertaken by the human brain, and how our feelings, thoughts, stimuli, and behaviors affect and are affected by cognitive processes involved in the resolution of ill-defined problems (Goldstein, 2008) such as the ones normally presented in product design and development situations. Even so, complete and deep understanding of how the mind operates and how decisions are made are far from being resolved.

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The process of developing products is understood in a practical sense with the rapid development of society as testimony for this, but the fundamentals underlying the process of designing new products awaits further study and insight. The act of being creative is a current gap in the field of cognition, and moreover, product design and development is by definition a creative process (Pahl, Beitz, Frelhusen, & Grote, 2007; Ulrich & Eppinger, 2003). In addition, product development is an open subject of study and is responsible for the best practices as well as failures in the market. As so, in a highly competitive world where product design skills are essential, the capacity to be creative and innovative is based on the very essence of creative thought. Although some of the written literature is concerned with techniques and methods to develop creativity (Kelley & Littman, 2004) or particular situations where creativity is found (Stefik & Stefik, 2004), only a small number of papers aim at comprehending further what is really involved in creativity (Amabile, 1996; Kuhn, 1962; Ogle, 2007). Furthermore, some interesting frameworks for creative cognition have been developed in the domain[4] of engineering design and cognitive psychology such as the ones proposed by Tang and Gero (2002), Hsiao and Chou (2004), Chusilp and Jin (2006) and Howard, Culley, and Dekoninck (2008), among others. The author has recently developed a framework of the ideation process, which we label as the "ideation framework" (IF). This descriptive framework of the design process, based on a dual cognitive-engineering perspective, is partly grounded on existing models from both fields and previous work performed (Marques, 2012). The main objective of the IF is to explain and modulate the front-end phase of product development. We also expect to contribute to answering the following research question:

> What is the consistence of the IF in explaining an empirical situation of a specific product development problem?

This paper starts with a brief literature review introducing the field of study and the background on the proposed framework. Then, the proposal of the new IF is revealed and detailed. Next, a case study using novice designers is presented, reporting the empirical findings of the use of the IF. Finally, the discussion section is drawn at the end of this paper, which also covers future research activities.

## 2. Brief literature review and background

In this section, we start with a brief introduction to the subject of study. Then, we will present some reference theories and frameworks in design and other design methods. Next, we will attempt a constructive comparison between all of them, serving as the basis on which the present research was built.

The literature concerning a summary of practices in engineering design is quite recent with the publications which consider the cognitive process within engineering design mainly from the last 4 or 5 decades with noticeable development in the 1970s and 1980s according to Coley, Houseman, and Roy (2007) and Cross (2006). Recent research has been in the domain of design cognition as discussed by Liu and Boyle (2009), with the clear objective of understanding both the creative process and the explanation of design cognition in terms of creativity. Cross (2000) reflected on the work within this field having evaluated the different characteristics of how a designer and a scientist achieved the best solutions for problem-solving. In his opinion, scientists tend to solve their problems by analysis while designers solve their problems by synthesis. A summary is that scientists use problem-focused strategies for problem-solving, whereas designers focus on the solution to a given problem. Dieter and Schmidt (2009) made an interesting comparison between the scientific and design methods in which the scientific method is mainly concerned with existing knowledge, scientific curiosity, hypothesis, logical analyses, and proof within a certain group of individuals that communicate between each other. Conversely, the design method relies on the state of the art, the identification of a need, conceptualization, feasibility analyses, and production and testing. The ability to design is based on human intelligence (Cross, 2000), a natural gift, and despite the fact that some individuals are more skilled in this activity than others, there is also the fact that design can be developed through educational background and practical experience. The success of design is strongly dependent on the competences of each designer, his/her personal creativity, the capacity for three-dimensional visualization, and the ability to present the ideas in sketches (also very dependent on the designer's intuition) *which is acquired during his/her professional experience* (Coley et al., 2007; Cross, 2000; Ullman, 1997). The practice of representing in terms of sketches, diagrams, and so on reveals an important role in the activity of design as mentioned by Goel (1995), Purcell and Gero (1998), and Cross (2000) and Lawson (2004), among others. On the other hand, design frameworks are basically classified into two classes: prescriptive frameworks and descriptive frameworks (Evbuomwan, Sivalogganathan, & Jebb, 1996). The prescriptive frameworks tend to take a broader view of the design process, covering step-by-step procedures and setting a way to accomplish a task. Conversely, descriptive frameworks bring into consideration the actions and activities developed during the design process, that is, what is really involved in the design activity and how it is actually done. Design frameworks (Cross, 2000) emanate from the experience of an individual designer and from studies carried out when the designs were created. The original solution passes through a process of analyses, evaluation, refinement, patching and repair, and development. It is a heuristic process, in which experiences are used together with general guidelines and rules of thumb that the designer hopes are in the right direction (Cross, 2000). Within the present scope and in the last ten years, some relevant articles have been published in engineering design research (Horvath, 2004). The volume of research work has been quite significant (see Howard et al., 2008), and in the present article, we have only identified and focused in-depth on relevant work for the purpose of laying the foundations for the framework to be proposed. The framework presented will therefore build on this past experience from the engineering design and the cognitive psychology community in a way that the author perceives as being more integrative. The following sub-sections describe some theories and frameworks relating creativity with design, as well as other design methods, that serve as the basis on which the present research was built.

### *2.1 Selected theories and frameworks in design*

Ideation can be seen as the creative process of generating, designing, and communicating new ideas (Graham & Bachmann, 2004; Jonson, 2005). It comprises all stages of a thought cycle, such as the case of product design and development activities, being particularly relevant to this study, the initial or sometimes called fuzzy front-end phase of an innovative design process. This sub-section covers four screened referenced theories in design and related with ideation that we have considered being relevant for the purpose of laying the foundations of the IF.

#### *2.1.1 The function-behavior-structure framework*

Gero and Kannengiesser (2004) proposed the function-behavior-structure (FBS) framework. According to Gero and Kannengiesser, agent-based designing systems (design research in Artificial Intelligence) are based on established frameworks and theories of designing that view the world as being permanent and well-defined. Nevertheless, empirical design research is not based on a static view of the world and thus not in accordance with the former point of view. Thus, the development of a computational design agent relies on a framework in which knowledge is not encoded, allowing for a changing world. The FBS framework proposed situates the act of designing at the interfaces between an expected world, an interpreted world and an external world, linked by six fundamental design processes: formulation, synthesis, analysis, evaluation, documentation, and reformulation. The design processes connect a designer's construction based on the function, behavior, and structure of a design object. Gero and Kannengiesser go on to explain how these processes link the different worlds and the sequence of their actions during a creative process. They place the expected world inside the interpreted world and these two inside the external world and depict each process as acting between each of the worlds.



### *2.1.2 Modifications by Howard et al. to the FBS framework*

Howard et al. (2008) presented a new framework for the creative design process based on the integration of the engineering design and cognitive psychology fields. For engineering design, Howard et al. classified the design activity into six common phases based on 23 recognized process frameworks of product development: establishing a need, analysis of task (meaning a planning of the downstream development, or a clarification of the customer needs, depending on the frameworks), conceptual design, embodiment design, detailed design, and implementation. From this classification, Howard et al. concluded that current design process frameworks are insufficient in terms of creativity, showing very few opportunities for creative ideas to emerge. From the cognitive psychology literature review, based on the analysis of a set of 19 process frameworks of creativity, the basic assumption found was that important areas can be identified and consequently grouped in four key phases: analysis of the problem, generation of ideas, evaluation, and communication or implementation. It was concluded from the study that the important areas in all the frameworks from both engineering and cognitive psychology are similar but are still in need of bridging. To close the gap between engineering design and cognitive psychology when dealing with creativity, Howard et al. (2008) proposed an improved version of Gero's FBS framework. Three additional creative components were then mapped onto this framework: analyses of creative tasks, generation of ideas, and evaluation. The components relate each design operation to the stages of the creative process, giving the view of the creative process from the domain of cognition and compared to the view of the design process from the domain of engineering design. Howard et al. argue that understanding the links between creative processes in the proposed framework may help designers to be creative, even if the typical design process is somewhat more erratic than some design representations tend to suggest. A composite definition of what a creative design output is was also presented, taking elements from the different design types proposed in engineering design and the creative outputs proposed in psychology.

### *2.1.3 The C-K theory of design*

The C-K design theory was presented in Hatchuel and Weil (2003) and is based around the interplay between two independent spaces: a concept-space and a knowledge-space, in Hatchuel and Weil's terminology. The interplay is mainly accomplished by moving from one space (the concept-space) to the other space (the knowledge-space). There are very few chances of conceptually shifting from one concept-space to another because the whole process is assumed to be developed within one concept-space. Little or no attention is given to the creative process leading to this interplay between concept- and knowledge-spaces, but the idea of the spaces between which the design is developed is worth pursuing (in design, concept and knowledge are interconnected) and is done in this article. Design is an actual move from concepts to knowledge, according to Hatchuel and Weil, and they go on to define different types of design, depending on what concepts or knowledge is used to create more knowledge.

In the C-K theory, the concept-space holds ideas (or propositions, according to Hatchuel and Weil) that are neither true nor false, meaning that they are exploratory concepts. If and when they become either true or false, that will immediately pass onto the knowledge-space which holds a kind of tacit knowledge. It has to be said that these spaces are designer-dependent. Each designer will have his/her own concept-space and knowledge-space. It is worth mentioning that the concept-space in the C-K theory is different from the one presented ahead in the present paper. The meaning of concept-spaces in the present paper will be explained further down when the IF is introduced.



#### *2.1.4 A cognitive activity framework of conceptual design*

Design and cognitive researchers normally use different approaches (observations of the design processes and analysis of design protocols) to explain how design teams behave in terms of creativity. Chusilp and Jin (2006) proposed a cognitive activity framework of conceptual design based on four cognitive activities: analyzing, generating, composing, and evaluating the problem. Analyzing the problem involves its understanding by exploring its requirements and constraints. The generating step accomplishes the generation of new ideas, including memory retrieval, association, and transformation – perceptual stimulation techniques. The composing phase refers to the evolution of initial ideas and their transformation into design concepts. Finally, evaluating – an exploratory cognitive process – is performed to ensure that a generated design concept is useful and relevant. It identifies three important iteration loops: problem redefinition (change the current definition of the problem, allowing the expansion of problem-space and solution), idea stimulation (a previously unused hypothesis might inspire the designers to produce new concepts), and concept reuse (use of previously presented ideas and concepts to create new ones). The existence of these iteration loops was experimentally verified, and Chusilp and Jin remark that creative design engages in more iterations than routine design and that constraints lead to more iteration.

### ***2.2 Other design methods***

This section covers two screened research methods in design. As mentioned before, only the most relevant work for the purpose of laying the foundations for the IF is presented.

#### *2.2.1 A cognitive method to measure potential creativity in design*

Tang and Gero (2002) have shown how empirical data gathered from protocol studies allows the measurement of novelty, value, and unpredictability in the different cognitive levels. Creativity is seen as an ambiguous concept because it is used to imply various things and abilities (cooking in a new way, inventing a new engineering law or solving old problems creatively). Examples of novelty in the design process are found in recognition of new relationships in sketches, new semantic meanings, or change of requirements due to client constraints (Tang & Gero, 2002). The analytical structure of the *Geneplore framework* (Finke, Ward, & Smith, 1999) was used as a methodology for the study of creativity in design. The Geneplore framework proposes two important phases to describe the creative thought: a "generative" phase and an "exploratory" phase. Through an experiment in which architectural design issues were explored using experts and novices, Tang and Gero (2002) concluded that creativity does not happen only internal to people's cognitive processing, but is rather located in relation to its context, at the process level, as proposed by Csikszentmihalyi's (1996) system framework of creativity. The system nature of design will also become explicit in the framework presented in this article where different systems within designs are proposed.



#### *2.2.2 The sensuous association method*

Hsiao and Chou (2004) developed a creativity method based on the sensuous skills of humans called the "sensuous association method" (SAM), allowing the production of creative ideas in a surrounding environment. Hsiao and Chou also proposed a creativity-based design process including three essential stages: divergence, transformation, and convergence (Jones, 1992), cited by Hsiao and Chou (2004). The SAM consists of four intrinsic personal human behaviors derived from the senses: (1) looking or information input, (2) thinking or inference and re-association, (3) comparing or extraction and restructuring, and (4) describing or creativity output, and one extrinsic behavior – stimulation or environmental inspiration, applied in the divergent stage. To prove the application of the proposed design process, methods of implementation (evolutionary thinking, correlation and interaction matrix, SAM, morphological analysis, and weighted generalized method) were used, and a case study of appearance design for an electric scooter was conducted. According to Hsiao and Chou (2004), the creativity-based process flows from a divergent stage, in which a problem-space is formed, to a transformative stage, in which a solution-space is generated, and finally to a convergent stage, in which viable sub-solutions are combined to form the final product. As conclusions of the study, Hsiao and Chou sustain that they have developed a method (SAM) that can be used to encourage designers' potential in producing innovative ideas. Later, Hsiao and Chou proposed a creativity-based design process, integrating various systematic design methodologies with the SAM, expected to provide a new approach in achieving aims of creative product design.

### ***2.3 Discussion on the previous theories, frameworks, and other design methods***

Having reviewed some frameworks, theories, and other design methods, we now attempt a constructive comparison between all of them.

Tang and Gero's (2002) framework present creativity as coming from a generative phase followed by an exploration phase, using problem constraints as a sort of system boundary. They recognize that these two phases are important and that designers constantly shift from one to the other during design. So, there is some iteration between generation and exploration with problem constraints serving as an evaluation tool. Hsiao and Chou (2004) proposed an interesting design process for designing new products, explicitly recognizing the existence of an initial divergent stage followed by a transformative stage and a subsequent convergent stage. The problem- and solution-spaces are introduced but no iteration loops are considered in a mainly linear process from problem to product. Jin and Chusilp (2006) studied mental iteration in design. Their mental iteration framework has an enormous potential to be used for new product development, especially as it explicitly uses constrained iteration as a necessary process to design. Howard et al. (2008) presented a framework that has great potential for this kind of study. Joining creative cognitive psychology and engineering design is the operating theme of the present work, and these authors went a long way in combining these domains. However, we consider the approach of Howard et al. (2008), based on Gero's previous work, to be somewhat complicated to follow in what regards its application to describe the creative process in product development. The flow of information from idea to generation is still puzzling, as their authors describe it, and lacking a practical example. Hence, a different approach will be presented in this paper. The C-K theory explicitly considers an iteration process between the concept- and knowledge-spaces. These iterations, however, move constantly from problem to the solution so that there are no feedback loops to eventually redefine the problem statement. The idea of different spaces is nevertheless reasonable in modeling design processes. Thus, the idea of problem-spaces, idea-spaces, and concept-spaces will be used for defining the mental-system boundary of an individual during design.

## 3. A proposal: the IF

The framework to be presented intends to deal with three aspects of design process modeling that presently call for the attention of the design community: linear versus iterative processes, heuristic versus algorithmic search for new concepts and the application of tools for decision-making with limited information within the design phase to evaluate competing concepts. Thus, the framework will deliberately blend rational and intuitive reasoning rather than forcing a decision between these two modes of thought as is sometimes done from antagonistic points of view (Brooks, 2010; Hazelrigg, 1998).

The first concern is directed at linear versus iterative processes. Simple design process frameworks have traditionally shown a linear perspective of the design activity. Some frameworks appear linear but incorporate iterations, while others explicitly state that the framework can accommodate iteration. According to some of these mostly linear frameworks, designing bears some resemblance to a production line, in which one task follows another, until a product is completed. This view of the design process has numerous advantages (in fact it has the same advantages of a well structured assembly line); most notably, it lends itself to process control, it provides an opportunity for milestones to be scheduled and design reports to be written and evaluated, costs to be assigned, and so on; however, it fails to capture the way in which creative minds design engineered artifacts. Apart from the fact that all design is evolutionary in the sense that it happens within an inspirational context, the need to constantly loop backwards for redesigning and testing is essential to the real learning that is inherent in the design (Whitney, 2004). The simplest linear frameworks, however, generally perceive such essential iterative nature as a waste of resources, therefore denying its appropriate role in the design process (e.g. Pahl & Beitz, 1984; Ullman, 1997). The importance of the iterative nature of design is played down by some but not all existing frameworks of design.

The second aspect, despite being studied among design researchers (Landry & Cagan, 2011; Linsey, Markman, & Wood, 2012; Taura, Nagai, & Tanaka, 2005) of the design process is the need to realize creative products as the output of the process. In our opinion, more effort can be devoted to better understand how creative ideas emerge during design.

It is now more or less acknowledged that creative thought has heuristic characteristics (e.g. Goldenberg & Mazursky, 2002). Heuristics are not based on traditional mathematical grounds as algorithmic procedures are. Nonetheless, algorithmic procedures are extensively used to frame creative thought. The major concern of using algorithmic procedures in creative design is that the former typically converge to a single solution while the latter (design) has no unique outcome.

The third concern encompasses the inherent difficulty in evaluating half-baked ideas that emerge whenever an artifact is being designed. Again, the problem is generally solved in formal frameworks with the help of some algorithmic method when most of the time the right decision can be made with a simpler heuristic approach and thus is used in actual design (Yilmaz, Seiferta, & Gonzaleza, 2010).

Although the interaction among team members in a design team is also a major research area, this framework will not address this issue. The cognitive approaches to the problem in hand are much closer to individuals than they are to design teams. Once initial assumptions about individuals are found to be accurate, design teams can be presented as future work, belonging more to the field of social psychology. Hence, this study will focus only on individual designers, not on design teams.

Before moving on to the explanation of the proposed IF, it must be noted that the outcome of the framework is not a new product or service, but merely a new concept for a product or service. There is a fine line between a very specific framework that is perfectly adapted to one situation only and a general framework that is valid to all situations. In our opinion, the further downstream one goes in the product design and development process, the more context-dependent any framework will become. Bearing this in mind, the present framework will be applied to the front-end of product design and development, where ideation has the strongest influence on the product outcome and where detailed information on the concept is not yet available (or needed) – this information will be generated further downstream. The framework is not algorithmic, in the sense that starting from the same assumptions and constraints one can reach very different solutions. It should be noted that most of the frameworks presented previously also share this characteristic. The IF is visually represented in Figure 1. While Figure 1



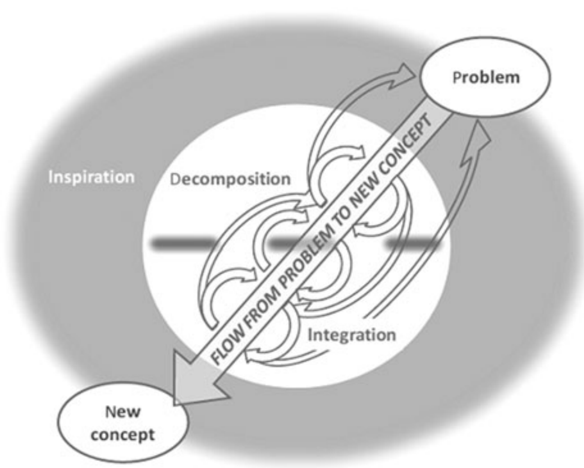


Figure 1. A general view of the proposed IF, from the decomposition of the problem (analyses) to the integration (synthesis) of a new concept.

depicts a straight arrow from a problem to a new concept, the framework is not linear and several iteration loops happen in the different domains, through which a concept or set of concepts flow. The framework encompasses three important domains: inspiration, decomposition (analysis), and integration (synthesis). A dashed line between the decomposition and integration domains means that there is no clear separation between the two. Within each domain, there are heuristics that act upon the flow of ideas to come up with a creative concept. These domains and heuristics will be explained in the following sections.

### *3.1 The inspiration domain*

Inspiration is needed for designing new products (see Stefik & Stefik, 2004) and driven by scientific discoveries, technology achievements, shortfalls in existing products and systems, opportunities from business and market surroundings, human needs, and others. While technological and scientific developments will act as a technology push to inspire the development of new ideas and products, the creative process can also be pulled by market needs (Stefik & Stefik, 2004). The inspiration domain is pervasive in the sense that there is no way in which one can say that it has no influence on the whole process of design. Different individuals or design teams will have different inspiration domains, depending on their educational and personal background and their lifelong experience. Within the inspiration domain lies not only the "problem-space" but also the "idea-space". The former encompasses the problem to be solved and all the information relating to it, while the latter accommodates all the possible ideas brought in to solve this particular problem. One can say that the idea-space needs at least to intersect the problem-space or no valid idea can be found to solve the problem at hand. This intersection as well as both spaces has to be in the inspiration domain if the problem is to be solved at all. We will call this intersection of "problem-space" and "idea-space" the "concept-space". Figure 2 shows a schematic of the spaces

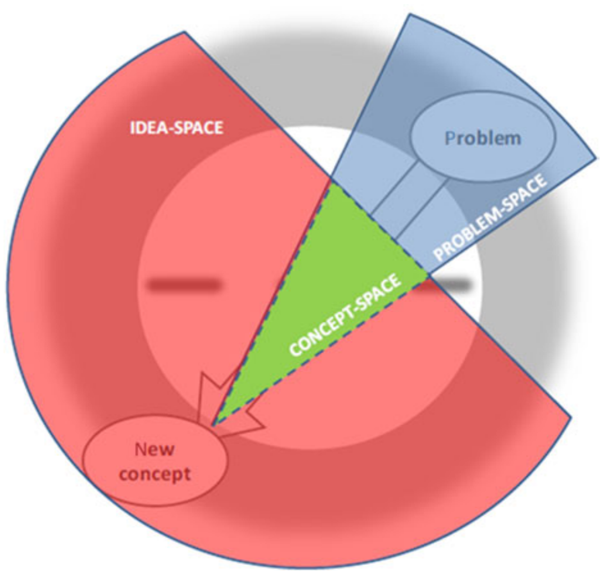


Figure 2. The problem-, idea-, and concept-space superimposed on the IF.

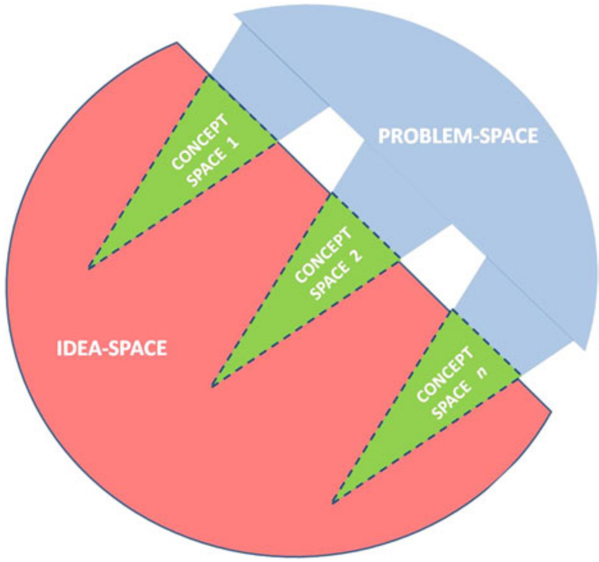


Figure 3. Multiple problem-, idea-, and concept-space (1 to *n*) on the IF.

superimposed on the IF. Some further related constructs are necessary to recognize when one thinks about a specific designer who may not grasp the whole of the problem- and idea-space. In this case, multiple problem-spaces and multiple idea-spaces could appear in the mind of the designer, thus originating multiple concept-spaces (see Figure 3). The concept-space(s) will therefore be formed at the intersection of the designer's interpretation of the problem-space(s) with the designer's interpretation of the idea-space(s).

### 3.2 The decomposition domain

Within the decomposition domain, the designer essentially breaks the problems, ideas and concepts into smaller subsets. There are a number of conceptual ways in which a designer can perform such decompositions. One can use a hierarchical or matrix decomposition from the problem to a set of specifications that are abstract and ideally independent of their physical materialization if there is one. The decomposition can be an abstraction of the problem to be solved, ideally setting measurable goals for the design to meet. In a typical product design and development process, this approach to decomposition would be similar to understanding and identifying customer needs and consequently setting specifications as goals for achieving customer satisfaction (Pahl & Beitz, 1984; Ullman, 1997; Ulrich & Eppinger, 2004); decomposition can also be accomplished as idealized functional requirements that the product is expected to fulfill. It is probable that different designers use different decomposition approaches and not unlikely that a given designer uses more than one approach. Most significantly, some designers are able to utilize several different decompositions simultaneously. An essential element of the IF process is that these abstract specifications or idealized functions will be taken up by the integration domain in the form of abstract information (see Figure 4). The arrows in Figure 4 mean possible iterations within the decomposition domain and the problem statement of idealized functions and target specifications for initial solutions and decompositions. Much of the decomposition

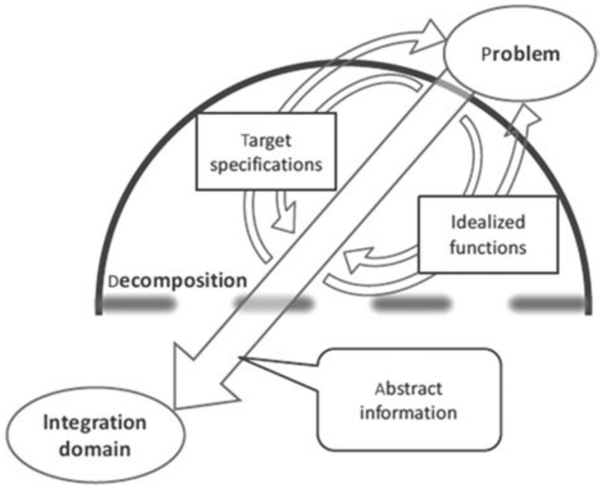


Figure 4. The decomposition domain of the IF.

may take place in the problem-space as the designer may not be thinking at this point of a solution to the problem. If however, the designer is already at this stage imagining a solution to the problem and is using this to construct the idealized functions or target specifications, then one has to place this activity between the problem-space and the idea-space.

### *3.3 The integration domain*

The integration domain uses all the information derived in decomposition to explore the idea-space in search of a solution to the problem (see Figure 5). The ideas that are formed in this process constitute the concept-space. The concept-space is part of the idea-space that has relevant information to the problem at hand; so, it is one of the possible intersections between idea-space and problem-space – in fact, every attempted idea is an intersection of problem-space and idea-space. The formation of this concept-space can be done with the help of, for example, the creative mechanisms (e.g. the use of analogy) proposed by Welling (2007) as heuristics to structure the creative process behind innovative ideas.

Evaluation ("EVAL" in Figure 5) of the ideas has to be done to proceed to further development. The evaluation is done by comparing the functions or the performance of the concept against the functions or the specifications derived earlier in the decomposition domain. This test can lead to three outcomes: first, the attempted concept performs all the functions and meets all the specifications, therefore becoming a possibly acceptable new concept; second, the attempted concept shows only partial fulfillment of both functions and specifications, but the designer believes that the concept can improve with some refinement, therefore going backwards on a specialization loop within the same concept-space; and third, either the concept is completely off target or successive specialization loops have failed to bring it to fruition and something more radical needs to happen – the designer must form another concept-space and start all over; this is called the generalization loop. Importantly, the generalization loop can involve a novel combination of two or more unsuccessful concepts.

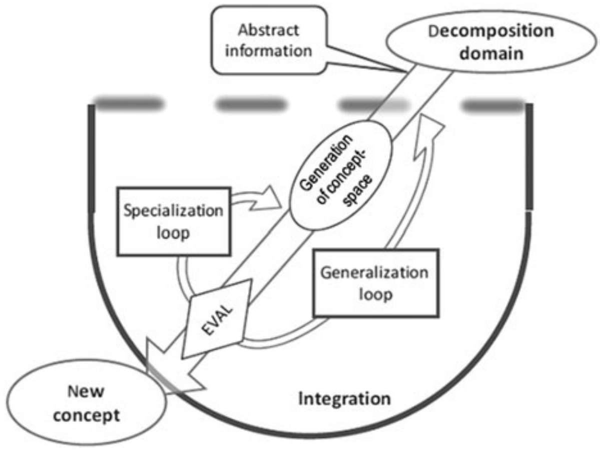


Figure 5. The integration domain of the IF.

### 3.4 *Further considerations on specialization, generalization, and evaluation*

There is evidence of specialization and generalization loops in the human mind thus pointing out the inherent iterative nature of product design activities (Ware, 2008). This iterative nature of the design activity includes feedback loops: the specialization loop – typical of concepts that are incrementally derived from existing products within the same concept-space – and the generalization loop – typical of concepts that may constitute breakthrough innovations in different concept-spaces. The whole concept of breakthrough innovation that most authors refer (e.g. Kuhn, 1962) to as being a rupture with something, can be seen in the context of this framework more like a natural consequence of the incapacity of the existing ideas (concept-spaces) to meet the expected results. It resembles more a big evolutionary step than a revolution. Specialization is a convergent loop of optimization: the idea will be refined and the concept-space optimized within this loop until no further improvement can be made. If no further improvement is possible, but the target specifications are not met, a persistent and creative designer will bring the generalization loop into play, introducing divergent thinking, redefining the concept-space and allowing for further development. These specialization and generalization loops also find an analogy in the duality of convergent and divergent thinking present when solving a design problem (Dym Agogino, Eris, Frey, & Leifer, 2005).

## 4. Empirical findings

In this section, an empirical examination of the IF is performed. The main objective is to understand which parts of the framework are consistent with empirical observations. Thus, the section begins with the characterization of the subjects under study and follows with the methodology used to pursue the proposed objective. The section proceeds with results, data analysis, and a summary of the main findings.

### 4.1 *Subjects under study*

The group of designers consisted of nine students (8 males and 1 female) from the 1st year – freshman – of the Mechanical Engineering degree from IST.[5] The group can be labeled as "novice designers." The designers received a small gift for having participated in the experiment. The experiment was performed in a design room facility at IST and the interview phase in the design studio facilities at IST. The language of the experiment was administered in Portuguese because it is the native language of all participants in this study. The design knowledge of the subjects under study is the one provided by the course "Technical Drawing and Geometric Modeling," where they learn the essential aspects of technical drawing with the use of CAD software and some basic design principles.

### 4.2 Methodology

Different types of techniques can be used for studying the cognitive behavior of design engineers (Coley et al. 2007) such as the thinking aloud method and respective protocol analysis (concurrent and retrospective), but elicitation techniques (see Christiaans, 1992) can also be used, such as structured interviews. We have decided to use structured interviews because we were trying to "elicit all knowledge related to a certain concept or model [the ideation framework] by continuously interrogating" (Christiaans, 1992, p. 96) the designers. This technique/strategy allows data on the structure of concepts and the reasoning/explanation of (part of) the mental model. Due to constraints in filming and recording the students during the problem task, we only audio recorded the interviews in the interview phase performed after the problem task. The "judgment" of the empirical examination was performed by the authors of this paper, having a background in Mechanical Design (Ph.D.) and expertise in the field (more than 10 years of practice).

The methodology used to achieve the objective of the descriptive experiment was organized in the following steps:

- Explaining the exercise to the designers: the design assignment or problem was – *To produce orange juice using a device designed by individuals (not power-assisted) and fresh oranges (citrine).*
- Performing the design assignment by the designers and answers to a questionnaire previously prepared: the designers were asked to spend an hour developing a sketch of a product to solve the previous design problem. Once this process was concluded, all the designers were interviewed and the sketch produced by each participant shown to assess memory retrieval in order to obtain a better understanding of how they did in the previous hour. Interviews were recorded. The interviewer was always present and could refine or rephrase the questions if the interviewee had doubts about the meaning of these questions.
- Data analysis: evaluation and description of the designer's spaces (see Table 3 in Section 4.4) and evaluation of whether the issues of iteration, evaluation, and generalization and specialization loops were described by the designers in the integration domain; in other words, a summary of the parts of the IF used – or not – by the subjects under study during the design assignment (see Table 4 in Section 4.4).

### 4.3 Questions used in the interviews

A structured questionnaire of 13 questions (see Table 1) was developed for this study (in Portuguese). Particular attention was given to the phrasing of questions. All the keywords of the framework were intentionally omitted from the questions and replaced by other terms with similar meanings.

Table 1. Questions used in the interview phase.

| Questions | The answers are potentially related to the following keywords of the IF: |
|---|---|
| 1. Describe how do you interpret the problem?<br>2. What questions did you ask yourself?<br>3. Did you think about the user's needs?<br>4. Do you know how your ideas arose? Do you know why these ideas emerged and not others?<br>5. What did you do with those ideas?<br>6. Are there aspects in these sketches that are more important in your idea generation and development than others? | Problem-, idea-, and concept-spaces |
| 7. Did you feel you had run out of ideas during the experience?<br>8. On a scale from 1 to 5, quantify the intensity of this "block" state?<br>9. Was it eventually relieved? If yes, in what way?<br>10. How did the solution to the problem arrive? Can you describe it?<br>11. Were there situations in which you felt like returning back in your approach to the problem? | Evaluation and iteration |
| 12. Did you focus on new ideas, that is, did you think in different ways?<br>13. Did you focus on the optimization of your original ideas? | Generalization and specialization loop |

### *4.4 Results*

This section starts with answers from the questionnaire (Table 2) and design outputs (Figure 6 (a),(b)) for a specific designer (Nr. 1) during the experiment. The text in Table 2 has sentences adapted from Portuguese to English and some sentences were abridged. The table was arranged concerning the answer for each question, the decoding of that answer, and the potential relation to a keyword of the IF (Tables A1 and A2 in the Appendix pertain to other two designers that participated in the study and showing similar structure). Next, we summarize results of the sketching and the interview phase for the nine designers involved in the study, more precisely, the "sentences" used to verbalize the problem-, idea-, and concept-space (Table 3), and an evaluation of keywords implicitly used by the IF, by means of the observation of the sketches and the analyses of the answers during the interview phase (Table 4).

As a summary of this section, one can say that the problem-space was identified by the designers, corresponding to each designer's interpretation of the problem. The idea-space accommodated all the ideas used to solve the problem, and the concept-space represents an intersection between the two former spaces. We recognized difficulties in decoding the problem-, idea-, and concept-space of one designer (Nr. 4, Table 4). We also recognized the existence of an ill-defined frontier between some idea- and concept-spaces as Table 3 shows some redundancies. Nevertheless, idea-spaces seem to be very important to produce concepts. For example, Nr. 1 developed, at least, two idea-spaces and consequently produced two concepts. The evaluation phase was identified by two designers, but we assume it has a step in our framework where difficulties in decoding and identify are verified. Designers typically characterize the process of design as a sequential/linear activity, but they confirmed to have iterated most of the times when asked. The concepts have evolved mostly within a specialization loop representing optimization and increments. Overall, the three spaces and the specialization loops are associated keywords to the designers when compared to the framework.

Table 2. Questions, answers, decoding, and relation to the IF's keywords for Designer Nr.1.

| Question | Answer | Decoding | Answer is potentially related to the following keywords of the IF |
|---|---|---|---|
| 1 | He produced two different solutions (see Figure 6(a),(b)). The problem was addressed by parts: (i) taking things apart and observing existent variables, (ii) the necessary work to solve each problem, and (iii) joining together all the parts for an overall solution. | Two different solutions and the existence of a decomposition. | Generalization loop, two problem-, idea-, and concept-spaces |
| 2 | He asked himself: What can go wrong? Not only regarding juice's production but also in terms of a future production process. He had in mind the objective, the number of variables and the easiest and less expensive solution. The main idea was to find a way to push down and rotating as traditional squeezers do. He thought about a "normal" and manual squeezer to start sketching. Next, he imagined something more elaborated: an engineered solution. | The main ideas to solve the problem, the use of analogy. The development of ideas. | The idea-space |
| 3 | It would have been important that the squeezer had a handle to make pressure on the orange and a manual crank for spinning motion. The problem of how to cut the oranges was leaved in standby. | The development of ideas and the initial concept. | The idea-space and concept-space |
| 4 | The next step of the solution was the introduction of a blade and the necessary space for it along with two cones for squeezing each part. A threaded part connected to a gear, rotating in opposite directions. Below, a filter and a glass for pouring the juice. Either he used some ideas or just threw them away. One idea was to make a lateral pressure on the orange but it would have led to spent extra energy. | Optimizing the process of ideas and sketching concepts. Evaluation of some ideas. | The idea-space, concept-space, and evaluation |
| 5 | Instead of a manual crank that might damage due to frequent use, a handle for pushing and twisting. Another thing to be introduced is a hinge, allowing cleaning/ removing the filter, orange-by-orange. | Optimizing the process of ideas and sketching concepts. | The idea-, concept-space |

(*Continued*)

Table 2 – *continued*

| Question | Answer | Decoding | Answer is potentially related to the following keywords of the IF |
|---|---|---|---|
| 6 | It was a process of development and optimization. The other solution is a completely different approach. It has a handle for pressing the orange and two parts with teeth shape. The first has a concave form, the second is convex. Rips should be introduced instead of holes for pouring the juice. | Optimization of the first concept. Building ideas for the second concept. | New idea-space and new concept-space |
| 7 | He did not feel blocked. The ideas were so many that he had difficulties in choosing one or two. It resembled a cloud in his head. The solution was completed by joining his best idea into a final one. | Evaluation of different thoughts. Optimization of the thoughts. Describing the solution with no apparent iteration. | Evaluation |
| 8 | N/A | | |
| 9 | N/A | | |
| 10 | The solution came as a systematic sequence of steps. He described it as: understanding the problem, establishing variables, establishing needs, and understanding he was squeezing an orange. He relied on a thoughtful market survey, observed existing solutions, and improved existent things, thus finding a way. | | |
| 11 | He focused himself in some type of a manual squeezer, those more traditional, saw the necessary forces, movements that were needed and “mechanized” the squeezer with fewer movements, the minimum energy. He mentioned returning back from the end of the concept to the beginning, collected ideas, discarding other, and improved some. | Describing again the solution, evaluating and iterated for apparent optimization. | Idea-, concept-space. Evaluation and iteration |
| 12 | He had ideas and to improve them he has focused on past problems: “what was wrong and what could be improved?” | Improvement by selecting things. | Specialization loop |
| 13 | Concerning the second solution, he tried to simplify the previous first solution or tried to address the problem in its simpler form. He saw the problem in a different way or from a different perspective, thus having new ideas. | Another approach to the problem, divergent thinking. | Generalization loop |

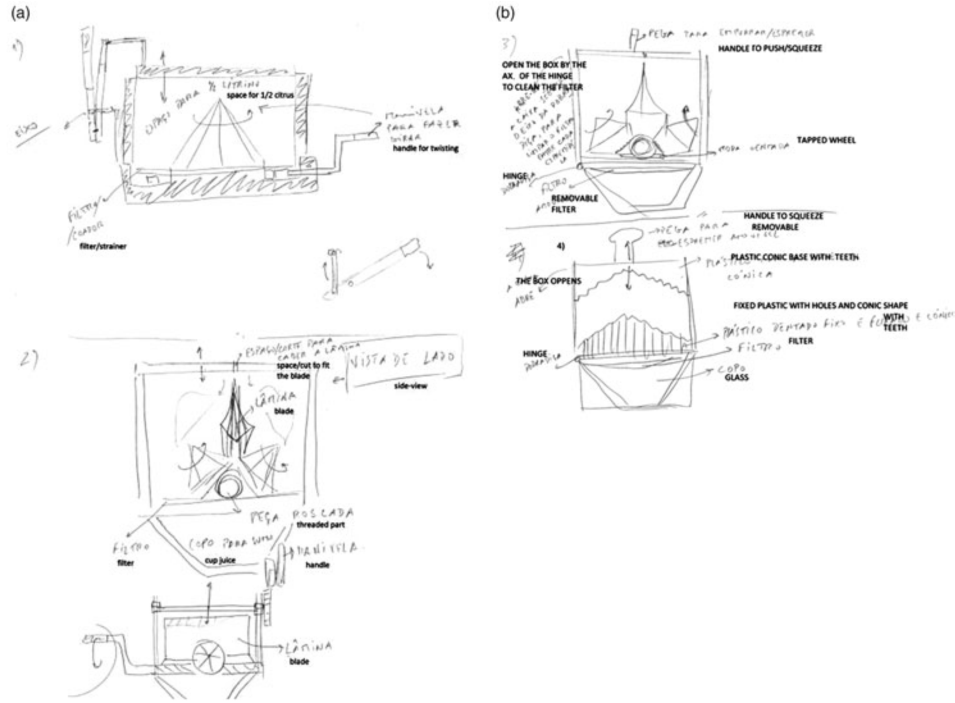


Figure 6. Sketch produced by Designer Nr. 1: (a) part A and (b) part B.

## 5. Discussion and conclusion

This paper addressed the objective of developing a conceptual descriptive framework of the ideation process in the front-end phase of product development, thus using a case study to evaluate the application of the IF in describing the ideation process. To do that, we have developed the IF based on important bibliography regarding the process of ideation. Then, we established a methodology based on a structured questionnaire and the observation of sketches. In more detail and to test the framework, we have used a case study during a specific design assignment employing a group of novice designers as we call it.

Table 3. Some sentences used to characterize the spaces.

| Type of space | Sentences mentioned during the interview |
|---|---|
| Problem-space | "Mechanical solution"<br>"Not electric"<br>"Easy to use"<br>"Functional and simple" |
| Idea-space | "Analogy to a manual solution"<br>"Pressure and rotation"<br>"Hydrostatic principle"<br>"Past experiences" |
| Concept-space | "Handle and cover"<br>"Crank for spinning and twisting arm"<br>"Pressure"<br>"Retainer" |

Table 4. Keywords of the framework used by the designers.

| Framework´s keywords/ Designer Nr. | Nr.1 | Nr.2 | Nr.3 | Nr.4 | Nr.5 | Nr.6 | Nr.7 | Nr.8 | Nr.9 |
|---|---|---|---|---|---|---|---|---|---|
| Problem-space | black | black | black | grey | black | black | black | black | black |
| Idea-space | black | black | black | grey | black | black | black | black | black |
| Concept-space | black | black | black | grey | black | black | black | black | black |
| Evaluation | black | grey | white | grey | white | black | black | grey | white |
| Iteration | black | grey | grey | white | white | black | black | black | grey |
| Specialization Loop | grey | black | black | grey | black | black | black | black | black |
| Generalization Loop | grey | white | white | white | white | white | white | white | white |

Note: Black – identified keyword; grey – possible identification; white – not identified.



As we have defined three spaces – problem-space, idea-space, and concept-space – within the proposed framework, we have shown how the designers interpreted these spaces using sentences to show it. Furthermore, these examples are very useful for understanding the importance of the spaces in design and ideation. As we saw, difficulties in constructing these spaces by an individual cause difficulties in coming up with ideas and concepts to achieve a task with success as in the case of one novice. It was also understandable that some novices typically followed the proposed IF in terms of keywords. Moreover, the case of evaluation, iteration, and specialization loops were considered elements of the framework as reported by some of the designers, but not all of them.

In fact, one should recognize difficulties in decoding the designers' thoughts regarding the concepts of evaluation and iteration as observed during the answers of the designers in the interviewing phase, thus contributing to difficulties in an in-depth analysis of some sketches and answers. As we see it, much of our design activity work occurs below the level of our consciousness and much of our "real and creative-thinking" is thus inaccessible to us, in particular when dealing with ideation processes. To overcome this problem, we expect to conduct new studies that could give us more detail about the ideation process using and improving this IF. In fact, we expect to further clarify the iterative flow of design using both specialization and generalization loops. We also expect to further clarify the initial flow of abstract information within the different spaces identified and the domains in question. To do that, we will need to clarify the connections between spaces and their interactions in the IF by means of concurrent protocols.

One has also observed that in general, novices used specialization loops to achieve a solution for the problem. This means that after attaining an initial solution to the problem, the novices tended to work within a specialization loop regarding the optimization, detailing, and improvement of a previously proposed solution.

Hence, this case study confirmed some of the previous studies performed concerning novice designers, such as the case of "trial and error techniques" (Designer Nr. 7 in Appendix) to generate an incremental design as already mentioned by Christiaans (1992). The novices tended also to suggest solutions almost immediately, not reporting much blocking situations and describing the process of design as sequential, thus reaching the next stage of development based on the previous one as observed before by Cross (2004). In typical open-ended design problems (Atman, Cardella, Turns, & Adams, 2005; Atman, Chimka, Bursic, & Natchtmann, 1999), novices' results show that they do not consider much alternative solutions as we have just observed. There was only one case reporting a novice using the generalization loop performing divergent thinking and coming up with another concept. We argue that the designer explored more than one solution to the problem and consequently involved generalization loops.

To conclude, the large absence of generalization loops has to be studied in more detail and in particular for designers with longer design experience as they are expected to use more generalization loops than novices. Future work would also include more studies using experienced designers, thus comparing them to novices.

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## Notes

1. Email: arlindo.silva@tecnico.ulisboa.pt
2. Email: elsa.h@tecnico.ulisboa.pt
3. Email: cmagee@mit.edu
4. A certain field of knowledge, such as art, science, or engineering.
5. Instituto Superior Técnico from the Technical University of Lisbon.

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## Appendix

### *Designer Nr. 4*

Table A1. Questions, answers, decoding and relation to the IF's keywords for Designer Nr.4.

| Question | Answer | Decoding | Answer is potentially related to the following keywords of the IF |
|---|---|---|---|
| 1 | He thought about the rotational motion provided by a handle, as seen in Figure A1, and in applying pressure to the orange, needing two persons for that purpose. The only way to get the juice was by pressure or rotating. | Sketching initial solutions | Possible idea-space |
| 2 | He asked himself what he should do to the orange do get the juice. | A problem to solve | Possible problem-space |
| 3 | He had to squeeze it and apply a rotational force. | Solution to the problem | Idea-space. |
| 4 | The idea just appeared to him by chance, something easy to store like a cube. He had no idea how he came up with this though; the ideas were continuous. | The concept of a cube | Possible concept-space |
| 5 | He had already answered. | | |
| 6 | He had already answered. | | |
| 7 | Initially, he referred to have no ideas because he just thought about an electric solution. | Possibly evaluating his ideas | Possible evaluation |
| 8 | The lack of ideas was average, he mentioned. | | |
| 9 | He started thinking about what a squeezer could do and formed ideas with that characteristics | | |
| 10 | He tends to believe that the solution is continuous. | No iteration | |
| 11 | No, he said. | | |
| 12 | He came up with what he described to be a new idea. He adapted the rotation of the squeezer, such as he had been developing a better product. | Describing an optimization | Possible specialization loop |
| 13 | He referred that the solution is not very practical in terms of operation but that was what he managed to do. | Difficulties in defining the problem and in achieving solutions | Possible problem-, idea-, and concept-space |

***Designer Nr. 7***

Table A2. Questions, answers, decoding, and relation to the IF's keywords for Designer Nr.7.

| Question | Answer | Decoding | Answer is potentially related to the following keywords of the IF |
|---|---|---|---|
| 1 | He interpreted the problem keeping in his mind what was necessary to make juice and her recent experiences on that. | Problem statement | Problem-space |
| 2 | He remembered when he was younger to be difficult to press and twist at the same time. | Past thoughts | Idea-space |
| 3 | He thought about what he could do to tighten the orange and discarded a twisting movement. | Initial solutions to the problem | |
| 4 | He tried to look up for something that helped him in pressing the orange with sufficient force to squeeze. It is easier to make two movements with one's hand than just pressing. | More solutions | |
| 5 | He wanted to prevent the strength that comes up after someone makes a downward force. | Detailing a solution to a problem. | Problem- and idea-space |
| 6 | The squeezer has a "normal" form in which he added a cover and a crank that allowed a constant force (see Figure A2). The novice mentioned that he had other ideas but they were much more complex. | The design of the solution | Concept-space |
| 7 | He did not feel had running out of ideas during the experiment. In fact, he thought about applying a twisting motion using a crank but he did not move into that direction. The other solutions were not important to him to be worthwhile of pursuing. | Explaining the reasoning of the solution | Possible evaluation |
| 8 | N/A | | |
| 9 | N/A | | |
| 10 | First, he reminded himself of creating a constant force in the cover and then looked up for the best position for it. He actually thought about two handles but it was not a practical solution. He thought about changing the angle of the crank but forces would not be equally distributed. He mentioned ending up with the initial idea as an error and consequence of others he had. | Explaining again the reasoning of the solution | Evaluation |
| 11 | He went back to change the site of the crank. | | Iteration |
| 12 | He tried to optimize what he already had. In a general design situation, he normally tries to optimize previous resources. The solution accepted in the end was the one initially rejected. | Optimization | Specialization loop |
| 13 | The general idea is based on optimization. | | |

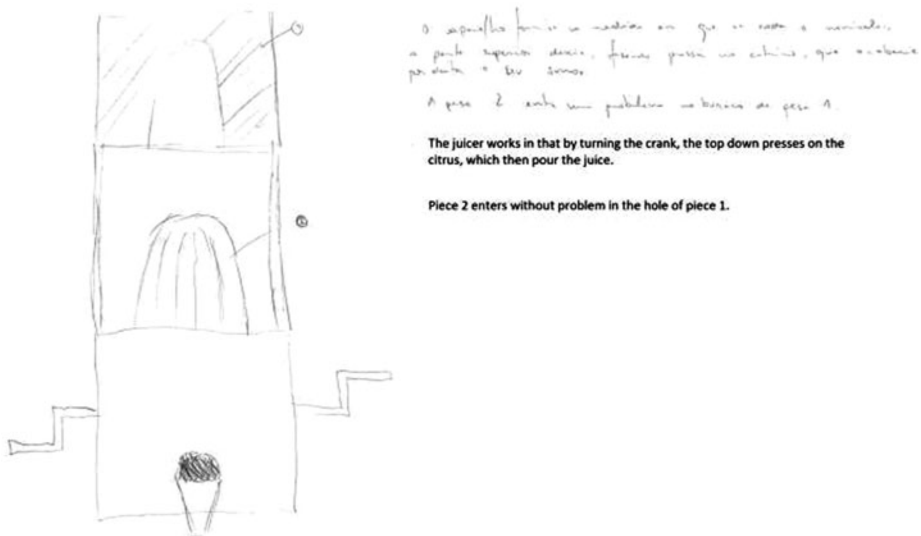


Figure A1. Sketch produced by Designer Nr. 4.

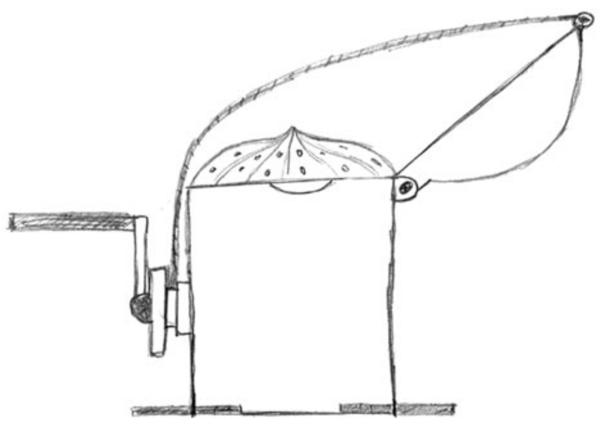

Figure A2. Sketch produced by Designer Nr. 7.