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Comparing Freshman and doctoral engineering students in design: mapping with a descriptive framework

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ABSTRACT
This paper reports the results of a study of engineering students’ approaches to an open-ended design problem. To carry out this, sketches and interviews were collected from 9 freshmen (first year) and 10 doctoral engineering students, when they designed solutions for orange squeezers. Sketches and interviews were analysed and mapped with a descriptive ‘ideation framework’ (IF) of the design process, to document and compare their design creativity (Carmona Marques, P., A. Silva, E. Henriques, and C. Magee. 2014. “A Descriptive Framework of the Design Process from a Dual Cognitive Engineering Perspective.” International Journal of Design Creativity and Innovation 2 (3): 142–164). The results show that the designers worked in a manner largely consistent with the IF for generalisation and specialisation loops. Also, doctoral students produced more alternative solutions during the ideation process. In addition, compared to freshman, doctoral used the generalisation loop of the IF, working at higher levels of abstraction. The iterative nature of design is highlighted during this study – a potential contribution to decrease the gap between both groups in engineering education.

1. Introduction
Design creativity is a motivating field of study and research (Badke-Schaub 2013). Indeed, creativity is not sufficiently clarified, particularly in the context of design (Bjorklund 2013); even so it is an interesting trait in thinking process of humans. Besides, design creativity and ideation are open subjects of study and responsible for the best practices as well as failures in the market (Kelley and Littman 2004). This type of research considers creativity in design as an option of attempting to identify its standard characteristics.

Also, understanding deeply design and creativity is a critical part of engineering design thinking and education (Dorst 2011), conferring a stimulus for this kind of study. In engineering education, one of the goals is to qualify students to become future expert engineers (Moreno et al. 2015). A good design knowledge is considered to be crucial for graduates, since design creativity is used in major tasks of engineering design practice (Crilly 2015). It plays a central role during engineering education, being considered a distinguishing activity, and playing a focus for engineering education in recent times (Dym et al. 2005; Lammi and Becker 2013).

One type of study, normally used in the understanding of design creativity, is the characterisation of two categories of groups: experts and novices. This allows further contributions to the enrichment of the curricula of engineering students throw reducing the gap between engineering novices and
engineering experts during engineering design problems (Ball, Evans, and Dennis 1994; McCracken 1997; Kavakli and Gero 2002; Silva, Henriques, and Carvalho 2009; Silva and Faria 2012; Silva, Fontul, and Henrques 2014).

For the purpose of this paper, one can label freshman students as ‘novices’ when compared to ‘expert’ doctoral ones. Previous studies on the subject (e.g. Christiaans 1992; Cross 2004; Bilalic, McLeod, and Gobet 2008; Bjorklund 2013; Crilly 2015) showed some important disparities between the behaviour of novice and expert designers. Novice designers use ‘trial and error’ techniques to generate a design incremental innovation instead of a breakthrough one, typically developed by experts and it has also been suggested that expert designers are better at problem outlining than novice designers (see for example Kim and Ryu 2014). As well, novices tend to suggest solutions almost immediately, after reading the problem statement. Conversely, experienced designers have a more preliminary observational evaluation of the problem, before the implementation of the final solution. As mentioned by Cross (2004), experts are different partly because their experience allows them to organise knowledge more effectively and in any subject. Cross (2004) has also observed that experts categorise problems based on their ‘deep structures’ (the fundamental principles involved) while novices base problems on their ‘surface’ features (what objects looked like). The author presented what he called a ‘depth-first’ approach to the problem-solving behaviour of novices, whereas experts commonly take a ‘top-down’ and a ‘breadth-first’ approach. Also, according to Ball, Ormerod, and Morley (2004), experts tend to be better than novices at problem-solving in their own field of knowledge, but are often no better than novices, when problems occur outside of that field. Atman et al. (2005) performed a comprehensive study to analyse the behaviour of freshmen and senior students using verbal protocol analysis. Results shown that seniors produced higher quality solutions, spent more time solving the problem, considered more alternative solutions, and made more transitions between design steps than the freshmen.

In this paper, one suggests the use of the ‘Ideation Framework’ (IF) proposed by the Carmona Marques et al. (2014) to study both groups during a design situation, since the past study was promising in testing the IF and understanding individuals in design. The motivation of this paper is to achieve a better comprehension of the design process, regarding two different communities of practice and normally studied among researchers in the field (Ball, Evans, and Dennis 1994). First studies are normally academia-based which allows further contributions regarding professional designers (Silva, Fontul, and Henrques 2014). It also allows to reduce the gap among these communities of practices, in particular which concerns new teaching strategies, helping educators to improve the curriculum of engineering design (Ting 2014). In this particular case, the iterative nature of design is highlighted, despite models of design development do not show this important characteristic (Pahl and Beitz 2007). Since the construction of the IF is intended to explain and ‘modulate’, from a descriptive point of view, the ideation phase – fuzzy front-end – of design, it can be used for testing and characterising groups of designers. One also expects to contribute to answering the following research question:

– Are there differences – if any – between the two sets, freshmen and doctoral, most explicitly the use of generalization and specialization loops in design?

This paper starts with a brief description of the IF. Then, a case study using freshmen and doctoral designers is presented, reporting the mapping of the IF to both groups in a design session. Finally, the discussion and conclusion sections show the differences found between the two groups and the characteristics to reduce the gap between both in engineering education curricula.

2. Related work: the ideation framework (If) (Carmona Marques et al. 2014)

The IF is visually represented in Figure 1 and is now summarily depicted. The IF is not linear, in the sense that several iteration loops occur in the different domains, through which a concept or set of concepts flow. The framework includes three important domains: inspiration, decomposition (analysis), and integration (synthesis). A dashed line between decomposition and integration 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 sub-sections.

2.1. Inspiration

Inspiration is needed for designing new products and driven by scientific discoveries, technology achievements, shortfalls in existing products and systems, opportunities from business and market surroundings, human needs, and others. The inspiration is pervasive, in the sense that there is no way in which one can state that it has no influence on the whole process of design. Different individuals or design teams will have different inspirations, depending on their educational and personal background and their lifelong experience. Within the inspiration lies not only the problem-space but also the idea-space. The former includes the problem to be solved and all the information relating to it, while the latter accommodates all the possible ideas brought in to solve a 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 inspiration if the problem is to be solved at all. One calls this intersection of problem- and idea-space the concept-space. Figure 2 (on the top) shows a schematic of the spaces superimposed on the IF. Some further related constructs are necessary, to recognise 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 2 – on the bottom). 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).

2.2. Decomposition

Inside decomposition, the designer essentially breaks the problems, ideas and concepts into smaller subsets. The decomposition can be an abstraction of the problem to be solved, ideally setting
measurable goals for the design to meet. An essential element of the IF process, is that these abstract specifications or idealised functions will be taken up by integration, in the form of abstract information (see Figure 3 – on the top). The arrows in Figure 3 mean possible iterations within decomposition and the problem statement of idealised functions and target specifications, for initial solutions and decompositions. Much of the decomposition 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 idealised functions or target specifications, and then one has to place this activity between the problem-space and the idea-space.

2.3. Integration

Integration uses all the information derived from decomposition, to explore the idea-space in search of a solution to the problem (see Figure 3 – on the bottom). The ideas formed in this process
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. The formation of this concept-space can be done with the help of, for example, heuristics – such as ‘analogy’ – to structure the creative process behind innovative ideas (e.g. Goldenberg and Mazursky 2002; Yilmaz, Seiferta, and Gonzaleza 2010; Linsey, Markman, and Wood 2012). Evaluation (‘EVAL’ in Figure 3) 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...
fulfilment of both functions and specifications, but the designer believes that the concept can improve with some refinement, therefore going backwards on a specialisation loop, within the same concept-space; and third, either the concept is completely off target or successive specialisation 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 generalisation loop.

2.3.1. Generalisation vs. specialisation
There is evidence of specialisation and generalisation loops in the human mind, thus pointing out the inherent iterative nature of design (Ware 2008). This iterative nature of the design activity includes feedback loops: the specialisation loop – typical of concepts that are incrementally derived from existing products within the same concept-space – and the generalisation loop – typical of concepts that may constitute breakthrough innovations in different concept-spaces. Specialisation is a convergent loop of optimisation: the idea will be refined and the concept-space optimised 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 generalisation loop into play, introducing divergent thinking, redefining the concept-space and allowing for further development. These specialisation and generalisation loops also find an analogy in the duality of convergent and divergent thinking, present when solving a design problem (Dym et al. 2005).

3. Methods and tools
During this section, the design assignment is mapped to the IF. The objective is to understand which parts of the framework modelled the empirical observations for both design groups. The section starts with the characterisation of the design groups 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.

3.1. Characterising the design groups
The group of ‘freshmen’ consisted of nine students from the 1st year of the Mechanical Engineering degree of the Technical University of Lisbon (UTL). The design knowledge of the group is the one provided by the course ‘Technical Drawing’ where they learn the essential aspects of engineering drawing with the use of CAD. The other design group – doctoral – consisted of 10 doctoral students in Engineering Design from UTL and University of Oporto. The doctoral are all M.Sc. in engineering areas, having good knowledge of the front-end of design, acquired in a discipline of their Ph.D., called ‘Product Design & Development’, and previous working experience in design. Please note that despite the two groups involved in the experiment all the designers performed the tasks individually.

3.2. Methodology
Different types of techniques can be used for studying the cognitive behaviour of design engineers (Coley, Houseman, and Roy 2007), for example, thinking aloud method and respective protocol analysis (concurrent and retrospective). Elicitation techniques can also be used, such as the case of structured interviews. Interviews are very useful for ‘eliciting’ all knowledge related to a certain concept or model [the IF], by continuously interrogating’ (Christiaans 1992, p. 96). This technique/strategy allows the understanding of data on the structure of concepts and the reasoning/explanation of a mental model. The methodology used in the design experiment was organised in the following steps (Carmona Marques et al. 2014):
• Explaining the exercise to the designers: the design assignment was ‘to produce orange juice using a device designed by individuals (not power-assisted) and fresh oranges’.
• Performing the design assignment and answers to a questionnaire previously prepared: the designers were asked to spend an hour developing a sketch 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. Interviews were recorded.
• Data analysis: evaluation and description of the designer’s spaces (see Table 4 in §3.3) and evaluation, of whether the issues of iteration, evaluation, and generalisation and specialisation loops, were described by the designers (see Table 5 in §3.3.1).

The judgement of the empirical examination was performed by four individuals (see acknowledgments), having background in Engineering Design (Ph.D.) and expertise in the field (more than 10 years of practice). Data obtained were ‘qualitative’ and ‘not quantitative’, thus no inter-reliability scale was performed between judgements.

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

3.3. Results
This sub-section starts with answers from the questionnaire (Tables 2 and 3) and design outputs (Figure 4 (a) and (b), and Figure 5) for two specific designers (Freshman #1 and Doctoral #1) during the experiment. The text in Tables 2 and 3 has sentences adapted from Portuguese to English and some sentences were abridged. Tables was arranged concerning the answer for each question, the decoding of that answer, and the potential relation to a keyword of the IF. Also, some illustrative answers from the questionnaire (Tables 4 and 5) and design outputs (Figure 6) for two other different designers (Freshman #7 and Doctoral #8) were summarised. One expects that the data from this four designers (two from each group) are sufficient to understand how data were analysed and detailed. In any case, data from other designers are available and can be obtained upon request.

Table 6 summarises results of the sketching and the interview phase for the two groups, that is, the ‘sentences’ used to verbalise their problem-, idea-, and concept-space. Table 7 shows a mapping of
Table 2. Questions, answers, decoding and relation to the IF’s keywords for Freshman #1 (adapted from Carmona Marques et al. 2014).

<table>
<thead>
<tr>
<th>Question</th>
<th>Answer</th>
<th>Decoding</th>
<th>Answer is potentially related to the following keywords of the IF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>He produced two different solutions (see Figure 5(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.</td>
<td>Two different solutions and the existence of a decomposition</td>
<td>Generalisation loop, two problem-, idea-, concept-spaces.</td>
</tr>
<tr>
<td>2</td>
<td>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 least expensive solution. The main idea was to find a way to push down and rotating as traditional squeezer do. He thought about a ‘normal’ and manual squeezer to start sketching. After, he imagined something more elaborated: an engineered solution.</td>
<td>The main ideas to solve the problem, the use of analogy. The development of ideas</td>
<td>The idea-space.</td>
</tr>
<tr>
<td>3</td>
<td>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 left in standby.</td>
<td>The development of ideas and the initial concept.</td>
<td>The idea-space and concept-space.</td>
</tr>
<tr>
<td>4</td>
<td>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.</td>
<td>Optimising the process of ideas and sketching concepts. Evaluation of some ideas.</td>
<td>The idea-space, concept-space, and evaluation.</td>
</tr>
<tr>
<td>5</td>
<td>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.</td>
<td>Optimising the process of ideas and sketching concepts.</td>
<td>The idea-, concept-space.</td>
</tr>
<tr>
<td>6</td>
<td>It was a process of development and optimisation. 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.</td>
<td>Optimisation of the first concept. Building ideas for the second concept.</td>
<td>New idea-space and new concept-space.</td>
</tr>
<tr>
<td>7</td>
<td>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.</td>
<td>Evaluation of different thoughts. Optimisation of the thoughts. Describing the solution with no apparent iteration.</td>
<td>Evaluation.</td>
</tr>
<tr>
<td>8</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>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, improved existent things, thus finding a way.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Continued)
He focused himself in some type of a manual squeezer, those more traditional, saw the necessary forces, movements that were needed and ‘mechanised’ the squeezer with fewer movements, the minimum energy. He mentioned returning back from the end of the concept to the begin, collected ideas, discarding other, and improved some.

Describing again the solution, evaluating and iterated for apparent optimisation.

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.

He mentioned returning back from the end of the concept to the begin, collected ideas, discarding other, and improved some.

Improvement by selecting things.

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.

Table 2. Continued.

<table>
<thead>
<tr>
<th>Question</th>
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<th>Decoding</th>
<th>Answer is potentially related to the following keywords of the IF</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>He focused himself in some type of a manual squeezer, those more traditional, saw the necessary forces, movements that were needed and ‘mechanised’ the squeezer with fewer movements, the minimum energy. He mentioned returning back from the end of the concept to the begin, collected ideas, discarding other, and improved some.</td>
<td>Describing again the solution, evaluating and iterated for apparent optimisation.</td>
<td>Idea-, concept-space. Evaluation and iteration.</td>
</tr>
<tr>
<td>12</td>
<td>He had ideas and to improve them he has focused on past problems: ‘what was wrong and what could be improved?’</td>
<td>Improvement by selecting things.</td>
<td>Specialisation loop.</td>
</tr>
<tr>
<td>13</td>
<td>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.</td>
<td>Another approach to the problem, divergent thinking.</td>
<td>Generalisation loop.</td>
</tr>
</tbody>
</table>

Table 3. Questions, answers, decoding and relation to the IF’s keywords for doctoral #1.

<table>
<thead>
<tr>
<th>Question</th>
<th>Answer</th>
<th>Decoding</th>
<th>Answer is potentially related to the following keywords of the IF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Doctoral #1 based idea Nr.1 and Nr.2, seen in Figure 6 in his experiences. He considered the Philippe Stark’s squeezer and the correspondent design – an insect structure – for starting sketching, but he mentioned that he did not want to pursue that concept, as he had identified some mistakes relative to it.</td>
<td>Two ideas for a squeezer. Use of analogy</td>
<td>Two problem-, idea-, concept-spaces. Generalisation</td>
</tr>
<tr>
<td>2</td>
<td>He remembered seeing idea Nr. 2 somewhere, but with a different shape.</td>
<td>Use of analogy to solve problems.</td>
<td>The idea-space</td>
</tr>
<tr>
<td>3</td>
<td>He did not have new brilliant ideas. Usually, what he does when he sketches, is having new ideas by remembering old products, their sketches and some edges.</td>
<td>The development of ideas and concepts</td>
<td>The idea and concept-space</td>
</tr>
<tr>
<td>4</td>
<td>He projected the user to himself asking: how is he going to squeeze the orange.</td>
<td>How to solve the problem</td>
<td>The problem-space</td>
</tr>
<tr>
<td>5</td>
<td>He played some scenarios in his head, visual representations and made some movements with his hands.</td>
<td>Development of concepts</td>
<td>The concept-space</td>
</tr>
<tr>
<td>6</td>
<td>He started sketching a simple shape to visualise the squeezer and made a simple structure composed by three or four parts. He imagined different kinds of products and understood their functions. He used the shape of one object into another one. This is very common, he referred. The form of idea Nr. 1 resembles a tree.</td>
<td>Development of concepts in term of functions, structure and analogies.</td>
<td>The concept-space</td>
</tr>
<tr>
<td>7</td>
<td>The expert felt block, because he missed ‘visual tools’ and sketching tools, necessary to proceeded with a concept.</td>
<td>Blocking situation in design and comparing to achieve a solution.</td>
<td>(Evaluation) &amp; Iteration</td>
</tr>
<tr>
<td>8</td>
<td>N/A</td>
<td>Two ideas for a squeezer. Use of analogy</td>
<td>Two problem-, idea-, concept-spaces. Generalisation</td>
</tr>
<tr>
<td>9</td>
<td>N/A</td>
<td>Use of analogy to solve problems.</td>
<td>The idea-space</td>
</tr>
<tr>
<td>10</td>
<td>Comparing what exists in the market is a strategy to achieve a new concept, he said</td>
<td>The development of ideas and concepts</td>
<td>The idea and concept-space</td>
</tr>
<tr>
<td>11</td>
<td>He did not see the process as a systematic sequence of steps.</td>
<td>How to solve the problem</td>
<td>The problem-space</td>
</tr>
<tr>
<td>12</td>
<td>He drew idea Nr. 2, but he came back to the notion of an orange, for achieving an improvement.</td>
<td>Improvement of a solution/idea/concept</td>
<td>Specialisation Loop</td>
</tr>
<tr>
<td>13</td>
<td>By doing this, he came up with another thought (idea Nr. 1).</td>
<td>Another idea</td>
<td>Generalisation Loop</td>
</tr>
</tbody>
</table>
the keywords implicitly used by the IF, by means of the observation of the sketches and the analyses of the answers during the interview (see Tables 2–5).

3.3.1. Summary of findings
As a summary, freshman typically characterised design as a sequential/linear activity, but they confirmed to have iterated most of the times when enquired. The concepts have evolved mostly within a specialisation loop, representing optimisation and increments in their design. Overall, the three spaces and the specialisation loops were associated keywords to the freshmen, when mapped to the framework. For the doctoral, typically, the spaces encompassed different ideas and general functions for a squeezer. Some also took into consideration ergonomic aspects. Most of the concept-spaces were analogy-based. While specialisation was reported in 6 out of 10 times, generalisation was applied most of the times. The generalist loop was widely connected to the number of sketches produced for each designer.

4. Discussion and conclusions
The main difference between the two groups was found to be that doctoral tended to use more generalisation than freshmen. There is only one case, in which a freshman has possibly used generalisation. Actually, doctoral used generalisation for producing more than one concept. Considering the group of freshmen, the developed squeezer was generally composed by a crank for twisting and a handle for applying pressure to the squeezer. This type of solution is based on specialisation. On the other hand, doctoral took a more general approach to the problem. Doctoral were typically interested in developing just different ideas for a squeezer. Even so, they did not forget the main functions and general requirements of the squeezer itself. The use of analogy was reported from doctoral in developing concepts. It was also clear that generalisation was an ideation process typically used.
by doctoral, while freshmen based their approach on specialisation. Moreover, doctoral reported more blocking situations than novices, and consequently iterated more times, while freshmen described the process of creativity, as a systematic sequence of steps. The reasoning for doctoral was based on iteration and the use of generalisation loops. Typically, the doctoral group was more difficult to be decoded than freshmen. This is another difference between the both groups and reflects the fact that doctoral worked at a higher level of abstraction (Welling 2007).

Figure 5. Sketch produced by doctoral #1.
Both groups confirmed some of the previous studies performed (Christiaans 1992; Cross 2004; Atman et al. 2005). For instances, Freshman #7 reported ‘trial and error’ techniques to generate a design. They also tended to suggest solutions almost immediately (not feeling blocked). On the other hand, doctoral typically had a more preliminary observational evaluation of the problem (generally feeling blocked), before the production of several concepts. Freshmen seemed to focus their minds in the solution for the problem presented, while doctoral students took a more general approach. Being this an open-ended design problem, doctoral considered more alternative solutions and possibly made more shifts between design steps than the freshmen. Finally, doctoral used analogy to solve their problems. To end, one should recognise that difficulties occurred between the concepts of iteration, specialisation, and generalisation, as observed during the answers of the designers, in the interviewing phase. This fact, contributes to difficulties an in-depth analysis of some sketches and answers.

This paper addressed the objective of characterising the differences between freshman and doctoral engineering students, during the ideation process of design. To do that, one has established a methodology, based on a structured questionnaire and sketch observation. Then, observations and answers were mapped with the IF, for decoding the process of design. This case study confirmed some of the previous studies performed about novices (Ball, Ormerod, and Morley 2004 and Atman et al. 2005), such as the case of trial and error techniques to generate an incremental design based on a specialisation loop of thought. The freshman also tended 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. In typical open-ended design problems, freshmen’ results shown they do not consider much alternative solutions, conversely experts work typically with generalisation, which is now confirmed and in accordance with recent studies regarding experts (e.g. Kim and Ryu 2014; Ting 2014; Crilly 2015). There was simply one case that reported a freshman using the generalisation loop and performing divergent thinking. One argues that the designer explored more than one solution to the problem in-hand and consequently involved generalisation loops. The above conclusions are important for understanding the gaps between both groups and reduce it in engineering design education curricula. More precisely, the iterative nature of design, presented during this study and focused by the IF, is a contribution to a better understanding of designers’ cognitive processes, thus decreasing the existent gap between experts and novices. One way to do this is to test the IF as a prescriptive framework.
Since the ideation framework is being positively tested as a descriptive framework, there are very good possibilities for it to become a prescriptive way of enhancing creativity in design; that is, if novices know and are taught to use correctly the IF, it can serve as instrument to achieve better solutions faster. To do this, a control group will test the possible use of the prescriptive framework against

**Figure 6.** Sketches produced by freshman #7 (on the top) and doctoral #8 (on the bottom).
a non-control group. The control group will be the one that will not know the framework, while the non-control group will know the framework. The idea is to check if the non-control group achieve higher/better rates of creativity when compared to the control group.

Of course the study presented so far as research limitations. First of all the amount of data gathered so far is not very high. In past studies, the study was limited to only novices but now an attempt has been made to also use experts thus providing an innovation of past studies (see for e.g. Carmona Marques et al. 2014 and Carmona Marques 2012). One believes that is a good contribution to both to understand the differences of the two groups but also to a further understanding of the IF as a descriptive framework of the design process and validity in both groups.

Future studies are planned using designers in industrial environments with the same purpose. Also, more studies involving larger groups of designers could improve the ‘validation’ of the IF and of course the reliability of the data obtained so far.

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Notes on contributor

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References


