A REAL-WORLD STUDY OF ANALOGICAL REASONING IN NOVICE AND EXPERIENCED DESIGN ENGINEERS

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ABSTRACT
This paper describes a study to understand the use of analogies by design engineers with different levels of experience in a variant design domain. Protocol analyses of twelve design engineers have been analysed to understand the functions and reasoning of the analogies. The protocols are real world data from the aerospace industry. The findings indicate a significant difference in both the use of analogies by novices and experienced designers and the reasoning from analogies. Novices were found to predominantly transfer information related to the form without explicit reference to design issues, whereas experienced designers tended to use analogies for problem solving and problem identification. Experienced designers were found to use the analogy to reason about the function of a component and the predicted behaviour of the component, whereas the novices seem to lack such reasoning processes.

Keywords: Analogies, design reuse, problem solving, reasoning, protocol analysis, design thinking.

1 INTRODUCTION
Engineering design is a complex activity where knowledge of previous projects and alternative solutions is invaluable. Experienced designers often refer to their past design experience and apply their knowledge to the current design context. Past design experience frequently concerns other products or components and hence can be thought of as analogy (within domain or close analogy). The use of analogies from outside of the domain, i.e. between domain analogies has been shown to input towards the novelty level of a solution [1]. Hence, understanding the use of analogy in design with experience, through real world data (studies in industry as opposed to laboratory settings) can increase our understanding of the design process and how analogy can be used by both novice and experienced designers. This paper presents such a study. First relevant literature related to analogies, the use or functions of analogies, and expertise level differences in design cognition are described in the following sections.

2 ANALOGIES
Analogy involves accessing and transferring elements from familiar categories (often referred to as the 'source') to use it in constructing a novel idea ('target'), e.g., in an attempt to solve a problem or explain a concept [e.g., 2]. In its most general sense, analogy is the ability to think about relational patterns [3] involved in most domains, although perhaps notably creative problem solving domains such as science, design and art. Analogical reasoning has long been viewed as central to intelligent thought and creative cognition [4,5]. In Engineering Design, as in other creative domains, analogy has been argued to be of special importance [6-8], as also evidenced by the many anecdotes of breakthrough inventions following distant analogies that exist in the design field. One of the most famous anecdotes is George de Mestral's development of Velcro after examining the seeds of the burdock root that had attached themselves to his dog. The sheer number of similar anecdotes of breakthroughs and inventions attest to the importance that is placed on analogy in domains of innovation [9,10].

2.1.1 Analogical distance
In analogical transfer, the 'distance' between the source and the target (the application of the analogy) may be large or small. For example, a designer developing a new aircraft jet-engine may make an analogy to other aircraft jet-engines (referred to as within-domain, or local analogies), or make an analogy to human anatomy or radios in developing the design (referred to as between-domain, or distant analogies) [see

11,12,13]. Some studies focusing upon analogy distance, have shown that:

- Local analogies involve greater superficial similarity between source and target, compared to lesser amounts of superficial similarity in distant analogies. This increase in superficial similarity may make local analogies easier to access [e.g., 14,15].
- Both local and distant analogies involve structural similarity. However, as distant analogies involve two vastly different bodies of knowledge, it may be more difficult to ensure successful transfer of solution elements in design problem solving from source to target as the domains may differ in multiple subtle ways [16].

The domain in which analogies are used may affect their distance, for example Dunbar [11,17] found that in real-world studies of expert scientists within the domain of microbiology, distant analogies did not play a significant part in discovery. Dunbar divided analogies into local, regional, and distant, and found that distant analogies were very rare in comparison to local and regional analogies. In design, Casakin [18], on the other hand, found that in an experimental study of visual analogy both novices and experts produced more between-domain than within-domain analogies. The experimental setup involved providing subjects with visual analogous displays and instructing them to use analogies, and this choice of experimental setup may have significantly affected the results.
Leclercq & Heylighen [19] conducted a think-aloud experiment in architectural design where subjects were provided with analogical cues (triggers) prior to providing a design solution. Half the analogies referred to these triggers. Overall the level of within domain analogies used was 43% with 57% being between domain analogies. In a real-world study of expert design analogizing, Christensen & Schunn [20] found a mixture of within and between domain analogizing [20] in a product development team working within medical plastics on making novel features on a variant design. In another real-world study of design engineers focussing on applying a known technology to a completely new product, Ball & Christensen [21] found a majority of between domain analogizing [21]. Both real-world design domain studies indicate that between domain analogizing is frequently used, but it is possible that the design domain and design task in question may in part determine the appropriateness of using within or between domain analogies. The more radical innovation type task [21] thus produced more between domain analogies than did [20]. It is thus possible that a variant design domain (such as the one studied in this paper) where the design task requires more reliance on past generations of products (so-called incremental designs) will show even higher levels of within domain analogies.

2.1.2 Fixation and analogical distance

The research on fixation and exemplar influence in generative tasks supports the notion that having or making examples available will bias people's creations toward features in those examples. A number of studies have shown how providing [1, 22-25] or retrieving [26] existing examples may inhibit generative creative processes. Examples, in this sense, lead to a higher proportion of property transfers from the examples into the subject's own work [27], and notably this result also occurs even when subjects are explicitly instructed that they should try to avoid such transfer [28]. Property transfer in generative tasks has proven robust across a variety of settings, including engineering design tasks conducted in laboratory environments [1, 22, 29]. Given objects from similar domains share more superficial similarity than objects from dissimilar domains, and since superficial similarity is one of the key driving forces of analogical access, this lead to the expectation that the presence or availability of within-domain exemplars increases the likelihood of within-domain analogizing [30]. In other words, the presence of within-domain examples may make it hard for creative problem solvers to break away from local analogies, since superficial similarity dominates access, and distant analogies will be less superficially similar than local analogies. Providing prior within-domain examples thus result in a bias toward creating features contained in those examples [31]. This was supported by Christensen & Schunn's [21] study of engineering designers, illustrating that the prevalence of between domain analogies in design conversations are reduced when referencing prototypes as opposed to design conversation that is unsupported by such prototypes. The result suggests that if exemplars are present, the designers are less likely to think about other domains than the present one. Lindsey et al.'s study with design students found that the representation of analogies also influences originality, analogies presented more generally facilitated the use of the analogy in novel solutions [32]. Dahl & Moreau's [1] further found that exposing students to one or several within-domain examples led to a lower proportion of between domain analogies being used compared to subjects who were not exposed to the examples. Furthermore, the proportion of between domain analogies used was a strong indicator of the originality of the resulting design. Apparently, the presence of one or more within-domain exemplars hindered students in producing original responses.

2.2 Analogical functions

Analogies may be used for solving problems or generating ideas for new solutions in design. But they may also be used for different purposes. Dunbar's [17,33] pioneering in vivo studies of real-world analogizing in science distinguished 4 types of functions for analogies: forming hypotheses, designing experiments, fixing experiments, and explaining concepts to other scientists (see also [30] for another classification of analogies in invention). Dunbar found that almost half of the analogies were explanatory. Such functions are, however, in part specific to science.
Christensen & Schunn [21] conducted real-world studies of engineering designers and found that analogies served three different functions: 1) explanation 2), problem solving and 3), problem identification. These are described further;

1) Explanation: Using analogies for explaining novel ideas to other team members may help ensure communicative alignment in design conversations.
2) Problem solving: These analogies are probably the main reason designers have been interested in analogical reasoning.

3) Problem identification: Problem identifying analogies play an evaluative part in especially the conceptual stages of design, when it is necessary to try to foresee whether a novel idea or concept would work under particular circumstances. In this case, analogy plays a part in evaluating novel concepts in that it is possible to transfer not only solutions but also potential problems from sources with which the designer has past experience.

Christensen & Schunn [21] found that the functions of analogies were distributed roughly evenly among these 3 categories, with 32% explanatory analogies, 40% problem solving analogies, and 28% problem identifying analogies. Ball & Christensen [21] extended these findings by pointing to an additional function of design analogizing: the function finding analogy, where existing forms are explored for novel functions. These real-world findings lend support to the hypothesis that analogies do not serve a single purpose in design.

2.3 Expert vs. novice differences in analogising

Research looking at expertise differences has been concerned with the nature of the problem representation [34]. The extended development and integration of problem structures ensure that experts are likely to focus on relevant aspects, whereas novices remain focused on irrelevant features, as studied in for example chess [35] and physics [36]. These and other studies have identified that experts tend to encode and represent information in a more integrated manner linked to deep domain knowledge. The difference in knowledge representation has been found to affect analogical access, with expertise levels enhancing the probability of successful transfer. Several studies have found that spontaneous access and use of analogies are associated with levels of expertise [37,38]. While novice knowledge representations are frequently based on superficial similarities between source and target, deep expert domain knowledge may ensure that purely structural similarities between source and target are noticed and transferred, even in the case of between domain mappings [15,39]. Experts may however also use superficial similarity in access, as this kind of similarity may act as a helpful heuristic in locating problems that are structurally similar [40].

In experiments on visual analogies, Casakin [18] showed that both experts and novices could identify and retrieve analogies from both between and within domain sources, but that experts made use of the between-domain sources in larger measures. Bonnardel & Marmeche [41] argued that whereas experts have large numbers of cases to base their reasoning on, novices have few.

Whereas this past literature on analogy expertise levels has primarily been concerned with the nature of the problem representation, and the effects on access and transfer, the present line of research will focus upon the functions of and reasoning involved in analogizing by experts as compared to novices. Novices may have fewer cases to base their reasoning on, but they also lack extensive and generalized or abstracted domain knowledge. As such, novices may in fact regard past within-domain cases as cognitive ‘safe-havens’, where, in situations of uncertainty, they may turn to knowledge and features from past examples for transfers into novel cases. Hence, novices may turn to past within domain cases for parameters and features to include in novel exemplars, rather than rely on abstracted or generalized knowledge. Ball, Ormerod & Morly [42] has made similar observations in experimental settings by showing how design experts mainly use schema-based analogies, where-as novices utilize case-based analogies. By changing only some features or parameters from past sources, past within domain cases may be seen by novices to act as a way to ensure that a future design will be functional with minor incremental alternations as compared to the source. The downside to this is that in lacking extensive domain knowledge, novices may transfer and utilize past within domain knowledge mechanically, without realizing problematic issues with transferring into novel exemplars that may share only part of the relational structure. Thus, novices, in relying on such past exemplars, may not be aware, of or reason qualitatively about, potential problems involved in making the transfer. Experts, on the other hand, will utilize past knowledge to support their reasoning about and evaluations of pre-inventive structures and ideas, by providing information about potential problems or solutions to problems in novel designs. For experts, past within-domain cases should act primarily as input to qualitative reasoning about design, rather than as mechanical transfers. De Groot states that experienced chess players rarely analyze a chess situation but recognize a situation [43]. Lawson interprets this understanding from the well-defined area of chess to the ill-defined area of design as the use of *precedents*, where the designers can recognize similar design situations [44].

One of the characteristics of novice designers is that they often approach a design task with a trial and error process, however experienced designers are able to avoid this process through the use of strategies [45-47]. Cross explains the ability of designers to frame the problem through the use of strategic knowledge [47]. Ahmed’s observations of experienced and novice designers led to the identification of a number of strategies that were used when approaching a design task and indicates that experienced designers can pre-evaluate solutions prior to implementation, hence avoid lengthy trial and error processes [45]. This pre-evaluate stage is also referred to as a simulation (described in the following paragraphs), which allow experienced designers to use analogies to evaluate and analyze solutions.

2.3.1 Mental models and analogies

One area looking at qualitative reasoning with long-term domain knowledge is research on causal mental models [4]. Mental models research has shown that participants rely on qualitative relationships, such as signs and ordinal relationships, and relative positions, speed or mass [e.g., 48-50]. When running mental models, people do not estimate exact values or quantities or carry out mathematical calculations in predicting system behaviour. Still, despite their lack of detailed quantifications, these qualitative reasoning strategies can be quite powerful, and has the tremendous advantage of allowing reasoning with partial knowledge, although at the expense of being somewhat inaccurate and imprecise [51]. For example, Trafton et al. [52] showed how weather forecasters build qualitative mental models from quantitative data to make quantitative predictions. Christensen & Schunn [53] showed in a naturalistic design engineering context how mental models were run under situations of information uncertainty, in order to try to turn that uncertainty into approximate answers. Ball & Christensen [21] extended that finding, in showing how analogies could serve several purposes in these mental models, by either starting up mental model reasoning, or serving as explanatory analogies later in the simulation. So far it has not been examined whether expertise level moderates the link between analogising and qualitative reasoning.

A number of empirical studies in engineering design have focused on understanding how experienced designers approach design tasks including their use of analogies. In relation to reasoning, novice designers tend to reason backwards and to use a deductive approach. In contrast experienced designers tend to reason forwards, and, when solving more complex problems, to alternate between forward and backward reasoning [54-57]. However, to our knowledge, there has never been a direct real-world comparison of analogical reasoning by experienced and novice designers. It is possible that experienced designers utilizes analogies as a starting point for running mental models in problem solving, by reasoning about the appropriateness of applying the source as an analog in the present context. Novice designers, however, may not have the same level of domain and background knowledge, and may thus be unable to make a reasoned analogy in terms of the past or predicted behavior of the resulting design. This is what we have pursued in the present study.

3 RESEARCH AIMS

The aim of this research is to understand the use of analogies in engineering design. In this research, observations were carried out in the aerospace industry, which can be described as variant design domain, with heavy reliance on past knowledge. The specific research objectives include:

- Understanding and identifying what purposes analogies serve in a variant design domain.
- Understanding differences, if any, between the uses and the distance there are in expert and novice analogising.
- Understand differences in design reasoning about analogies between experts and novices
- Understanding differences, if any, based on the stage of the design task being observed.

Analogies were hypothesized to be used for different purposes by novices and experienced designers. Design novices may rely on past within domain cases that are known to work, as 'cognitive safe-havens' from where they may draw information into novel designs, whereas experienced designers are expected to primarily utilize past within domain cases in order to identify or solve potential problems with novel cases. It is expected that reasoning about the transfer (by providing predictions, evaluations or the like) may be uncommon with the novices, however, this should be frequent for the experienced designers utilization of analogies. As such, experienced designers should use more qualitative reasoning in connection with analogies, than novices.

As such, it was hypothesized that:

- novice within-domain analogizing would be characterized by fewer references to problem identification or problem solving, but rather would frequently act merely as a mechanical process where information from past cases would be transferred into novel ones.
- experienced designers, on the contrary, should utilize within-domain analogizing for identifying or solving problems, and these should primarily be used in the qualitative reasoning of the designer. That is, parameters and geometrical features are not transferred mechanically, but rather past cases are used in the qualitative reasoning of the designer in solving or identifying potential problems within the new design context.

Therefore, the functions of, and reasoning about, past exemplars (analogies) is expected to differ between experienced and novice engineering designers.

4 RESEARCH METHODOLOGY

4.1 Data collection

Protocols of 12 design engineers working individually on their own design tasks in the aerospace industry were utilized for this research. The observations were originally carried out to investigate differences between experienced and novice design engineers when approaching design tasks [45]. The participants were selected based upon their experience, six experienced designers and six novice designers were observed. Those with fewer than two years of experience were defined as novices and those with more than eight years of experience as experienced designers. Please note that in most studies of expertise level, novices are undergraduate or graduate students, but here novices are practicing design engineers who have completed their eductaion but with limited experience.

The design engineers were observed, while asked to think aloud, when working on real design tasks, i.e. the tasks were set by the company as opposed to artificial design tasks set up for research purposes. The design tasks studied are all variant designs from the aerospace mechanical design domain and usually involve incremental innovation to extend existing product solutions. The design tasks observed were at both conceptual and detailed design phases of the product development process. The designers worked in two different stages of design: conceptual and detail design, with 3 experienced and 3 novice design protocols from each stage. The stages were defined by the company.

The designers were observed in their own environments whilst working on their own design tasks. An interview of 15-20 minutes followed each observation to provide background information about each design task and each designer's experience. The designers were observed for periods of between 90 to 120 minutes, but this did not restrict the total amount of time they could spend on their particular tasks. It simply defined the duration of the observations.

All the observations were audio-recorded and the designers were asked to verbalise their thoughts. To avoid biasing the results, no expected results were communicated to the participants. The observations were transcribed from the audio-recordings. Segmentation was done on a line-by-line basis, amounting to a total of 1680 segments for the novices and 1687 segments for the experienced designers. The amount of data for experienced and novice designers was thus almost identical. From these transcripts segments related to analogies were identified. The coding employed for the analogy segments are described in the following section.

4.2 Coding

The protocols were coded for presence of analogies by applying Christensen and Schunn's [20] approach. A segment was coded as an analogy if a designer referred to another source of knowledge and attempted to transfer concepts from that source to the current task. Analogies were coded for 'analogical purpose' (i.e. the goal or function of the analogy) using an adaption of the above coding scheme [20]. This adapted scheme categorised analogical purpose in terms of: (1) *problem identification* – noticing a possible problem in the emerging design, where the problem was taken from an analogous source domain; (2) *solution generation* – transferring possible solution concepts from the source domain to the target domain; and (3) *explanation* – using a concept from the source domain to explain some aspect of the target domain. A fourth code was added to the original coding scheme, (4) *direct transfer* – basing a novel design directly on an existing design without identifying or referencing problems with the source. With the addition of this category to the scheme it was possible to code all analogies within the transcripts.

All analogies were also coded for 'analogical distance' using a binary categorisation scheme where within-domain analogies involved mappings from sources that related to tools, mechanisms and processes associated with the aerospace domain, whilst *between-domain* analogies involved mappings from more distant sources.

Segments from the transcript were also coded for the reasoning processes employed and the stage of the design problem solving process. The coding scheme employed is adapted from one used to understand question asking during design activity [58]. The reasoning codes included:

- *Form* (F), defining of the geometry and material of the concept.
- *Intended Behaviour* (IB) also referred to as function, the desired behaviour of the design, product, assembly, component, material or feature.
- *Predicted Behaviour* (PB) predicting how a concept/ product will behave.
- *Observed Behaviour* (OB) references to known behavior of past designs.

A final coding employed was used to code the stages of the problem solving process for which the analogies were employed. The three stages of generation, analysing and evaluation were selected, based upon Gero's model [59].These are defined together with the reasoning process expected as [57]:

- Generation- synthesis phase of designing, including defining form, material, etc. of a component. Ideally, the defining of form is linked to an understanding of the function. Hence, a reasoning process moving from intended behaviour to form is expected (IB- F).
- Analysis- analysis of a solution, for example through predicting the behaviour of a form. Hence reasoning process (F-PB) are expected,
- Evaluation- the evaluation of the solution for its purpose. Hence, the reasoning process of comparing predicted behaviour to intended behaviour is expected (PB-IB).

4.2.1 Inter-rater reliability

Each author independently coded half of the transcripts. Three transcripts (25% of the data) were randomly selected for reliability coding, and coded independently by both authors. For each code a reliability Kappa was calculated, and all codes reached a satisfactory level, i.e. Kappa >.70 (see Table 1).

	Kappa
Analogy	.880
Analogical functions	1.00
Reasoning	.714

Table 1 Inter-rater reliability

5 RESULTS

5.1 Frequency of analogies

The number of analogies totaled 35 across the 12 transcripts (M=1.5 analogies per hour of verbal data). The number of analogies ranged between 0 to 8 analogies per transcript. Experienced designers produced 19 analogies, with 16 for the novices. No significant difference was found in the number of analogies referred to between novices and experienced designers. This is contrary to literature [41], however a significant difference in this paper is that the design engineers are not students, but practicing engineers, hence even the novices have had exposure to real world projects and greater domain knowledge.

5.2 Analogical distance

All but a single analogy were within domain in the present study, thus indicating that the design domain (original design or radical innovation vs. variant design or incremental innovation) may indeed pose important restrictions on the distance of the analogies used. A variant design domain, such as that observed, showed that the designers relied heavily on products from the same domain, without resorting to analogies from other domains. As such, support was found for the hypothesis that in real world design, incremental innovation design tasks lead to more within domain analogies, while previous research has shown that in more radical innovation design tasks, between domain analogies become predominant.

5.3 Purpose of analogy by expertise level

The purpose of the analogies were distributed across the categories with:

- 10 instances of problem identification
- 10 instances of problem solving
- 15 instances of direct transfer
- No explanatory analogies were found.

In order to examine the ratio of analogy purpose by expertise level, a chi-square was conducted. Due to expected counts less than 5, the problem identification and problem solving categories were collapsed, to be able to look at the interesting relationship between the direct transfer category and the other categories relating to identifying or solving design problems. Results indicated a significant difference ($\chi^2(1)=4.64$, $p<.05$), with experienced designers utilizing problem solving or problem identification analogies more, whereas novices more frequently utilized analogies for direct transfer. The below excerpt illustrates the way novices used analogies in the present context (refer to Table 2, Excerpt of Transcript: Novice, N.B: reference to products have been made anonymous).

Excerpt of Transcript: Novice:
"Right so here we have got the HP2 compressor blade from Engine X. Take a closer look, what they used to do so far is to print something like what you have got behind you, basically you chose all the different views of the blades to understand how the geometry has been done. Basically what I need to do is using the same type of geometry; I'll try calculating the weight of the blade for my engine. So what I do is I take the Engine X blades. I break it down into basic geometry's. For each geometry I can easily calculate the volume, and then add everything up to get an overall volume of the blades. Knowing the density of the blade, you can calculate the weight of the blade. And you can basically check it because I know the weight of the blade for Engine X. The weight of the blade turns out to be close enough as I know the method is correct. So we can use it for my engine."
Excerpt of Transcript: Experienced designer:
"…56 times 31.8 is 1780 m squared where this one is 59.4 times 37.8 which 2245, so you see this blade is actually quite bigger than a Engine X rotor blade which immediately tells me we are gonna be in trouble, because Engine X rotor one blade has trouble holding on to the disc that we have to take and this one bigger and gonna be faster. Now look at these surface area ratios 2245 by 1780 and I would say that my blade is 26% bigger. Ratio of surface areas equals 1.826, therefore the weight of aerofoil equals xx times .0584 0.0737 pounds per aerofoil. Now I already knew I would be in trouble with this blade…"

Table 2 Excerpt 1. Use of analogies

In this analogy, the past design is used as a base for working on the novel design, without reference to potential problems with the transfer, or why basing the novel design on this particular analogy seems warranted in the present context. In this sense, a direct transfer takes place, where the novice may continue working based on a past design that is known to be functional. The designer has undertaken a generation task, but does not consider the function, behaviour or issues involved, instead simply moving from past form to current form (F-F). Counter this with the way experienced designers typically utilized analogies (refer to Table 2 Excerpt of Transcript: Experienced designer). Here the experienced designer uses his past experience with the source analogy to predict behavior (PB) in the novel design, and identify potential problems with that design. Hence the designer undertakes an analysis of the solution moving from Observed Behavior-Predicted Behavior to Form (OB-PB-F) reasoning about the source analogy knowledge and identifying problems is at the core of the analogy's function – the experienced designer does not merely transfer structural requirements from source to target i.e. Form-Form (F-F)– but also transfers information related to, in this case, potential problems with the design.

5.4 Reasoning in relation to analogizing by expertise level

The most prevalent design reasoning strategy in relation to analogies was Form→Form, F-F, (20 instances), with the remaining 15 analogies involving one or more instances of observed behavior, intended behavior or predicted behavior of the design.

To examine the relation between qualitative design reasoning and analogizing, a chi-square test was conducted, where the F-F reasoning was compared to reasoning involving IB, OB, or PB by expertise level. The results indicate a significant difference ($\chi^2(1)=6.99$, $p<.01$), with novices reasoning more frequently by simply mapping form to form, whereas experienced designers use the analogies to reason about past observed behavior in the previous design, by making predictions to future designs, or by looking at the functions or intended behavior of the product. This may be further substantiated by dividing reasoning strategies up by OB, IB, and PB (see Table 4). As can be seen, experienced designers more frequently use the reasoning strategies related to both observed behavior, intended behavior and predicted behavior. Despite the low numbers this is even significant for IB (two-tailed Fisher's exact test comparing FF to IB, $p<.002$)

Designers	F→F	Other involving		
		OB	IB	PB
Novices	13	2	0	2
Experienced	7	6	9	6

Table 3 Reasoning in relation to analogies by expertise level. Note: OB, IB and PB are not exclusive codes as a single analogy may contain reasoning about two or more of these. However, what is apparent is that no instances of using IB (i.e. the function) were observed with the novices. They predominantly use analogies to transfer geometric characteristics.

The excerpts presented in Table 4 illustrate how novices and experienced designers respectively tended to reason with analogies, and are discussed here.

Novice (refer to Table 4 Excerpt of Transcript: Novice):

Here the novice simply utilizes an existing form to calculate a parameter for the new form, i.e., simple form-to-form (F-F) reasoning. Contrast this with how a typical experienced designer would reason with analogies:

The experienced designer here (refer to Table 4 Excerpt of Transcript: Experienced Designer) utilized an analogy based on past observed behavior (OB) to predict behavior (PB) in the novel design, followed by transfer of form (F) to the new design. Such reasoning was typical, and lengthy in the experienced designers line of reasoning about analogies, involving predictions, intended behavior of the design and past observed behavior – whereas such reasoning was not typical of the novices. Rather, the novices tended to mechanically and directly transfer information from a source (without considering it's validity or problematic issues as a source) to the target. The novice designers tended to transfer geometrical parameters, often simply reusing a component. On the other hand, the experienced designers tended to transfer: issues of past designs to the current context; behavior, including using known behavior to predict the behavior of the current solution and; if the geometric features where transferred, this was together with an awareness of issues which were different between the analogy and the current context and hence could be used to adapt the design solution.

Excerpt of Transcript: Novice:
"So we got 9.102 inches, which is 48.31 millimetre for Engine X, and 34.61 for Engine M, square it, and the scale factor will be 1.948. So basically I need to multiply this number by this area, which will give me the approximation for cross-section are of my engine. I need to enter tip and radius as parameter…"
Excerpt of Transcript: Experienced designer
"The other thing I know is that based on my knowledge of the Engine X and L, the seal is more a flow discourager than a seal. The pressure on both sides of the seal is the same, it is more to stop the air on the inside being pumped out by the centrifugal action. Even it were to crack it would make little difference to the performance effect on the part. So I have no problem with it being a class X forging."

Table 4 Excerpt 2: Reasoning from analogies

5.5 Experience level in relation to stage of problem solving process

The data were examined to understand if novice and experienced designers use analogies at different stages , i.e. generation, analysis and evaluation, of the design problem solving model (refer to (59)). It was found that there was a significant difference in the use of analogies for evaluating the current concepts (two-tailed Fisher's exact test comparing Pure Generation to Evaluation, $p<.0001$). Only the experienced designers used the analogies to evaluate their ideas though understanding of the issues, or behavior of both the analogy and the current design context (see Table 5). Novices predominantly used the analogies to generate concepts, whereas experienced tended to use the analogies to generate concepts and also evaluate or analyze them.

Designers	Analysis	Evaluation	Generation	Generation combined
Novices	2	0	13	2
Experienced	7	11	8	7

Table 5 Stages of problem solving to analogies by expertise level.

5.6 Conceptual vs. detail design by analogy function

To examine whether the purpose of analogies varied by stage in the design process, a Fisher's exact test was conducted with problem identification and problem solving collapsed as one category, and direct transfer being the other category versus stage in the design process (conceptual vs. detailed design). The result of the two-tailed Fisher's exact test was significant ($p<.002$), with conceptual design containing all the direct transfers, as opposed to none in the detailed design. This was the opposite to what was expected.

6 DISCUSSION AND IMPLICATIONS

The results of this research were derived from data focusing on a variant aerospace engineering design of a complex product, and some of the findings may be related to this. For example, as only one between domain analogy was found, the variant design nature and the high emphasis on regulation of the industry may explain why all the remaining analogies were within domain analogies from the aerospace industry. No examples of an explanatory use of analogy was found, however this may not be so surprising as the designers were working individually, and previous reports on analogy serving explanatory functions have come from team environments.

An unexpected finding was observed in that all the examples of using the analogy for direct transfer (i.e. not directly problem solving or problem identification) were observed in the conceptual design phase, although predominantly by novices. This may be due to the complexity of conceptual design, due to the number of decisions to be made (Domeshek & Kolodner, 1997). The design process employed at the company where the observations took place clearly separates concept design from detailed design. The concept design phase often concerns more than one system of the engine, and hence these novices may be using analogies as a 'cognitive safe haven' which may serve the additional purpose of offloading cognitive computations thereby mentally reducing complexity by relying on aspects of past known-to-function exemplars, thus freeing up cognitive resources to design on fewer novel elements at a time.

The 'cognitive safe haven hypotheses' of novice designers' direct transfer of analogies (from Form to Form) thus involves several components: 1) within domain analogizing is carried out under situations of uncertainty, in order to reduce that uncertainty. By simply reusing a design, including geometry, the novice designer may reduce the risks involved as past designs are tested and certified than if no analogy was used. The closer the analogy is to the original (source) design, the easier it is to assess the risk [61]. 2) The analogy from source to target is carried out without reasoning about potential problems with making the transfer to the present context. The novice designer may not have been involved in the past design and hence not be aware of the rationale of the design decisions, thereby limiting the transfer to a direct unreasoned or untested transfer, as it is difficult to know how to change the design and how to assess the impact of the change. As such, the novice designer assumes that a direct transfer can take place, rather than critically reason about and examine such an assumption (which seem to be the experienced designerly way).

The exemplar influence on generative tasks literature has previously noted that relying on within domain examples may lead to reduced originality in the resulting design. The present 'cognitive safe haven' hypothesis further suggests that novices may reduce the usefulness of their designs (compared to experts) in their direct and uncritical approach to analogical reasoning. While it has been argued that the use of within domain analogies may overall increase the usefulness of the design solution by mapping to sources that share a great amount of both superficial and structural similarity [62] the present results suggest that novice designers may be less capable of carrying out the required analogical reasoning on potential differences than experienced designers. 'Originality' and 'usefulness' are the two standard elements contained in the definition of creativity [63], and the use of within domain analogies may thus limit the creativity of novice designers' solutions compared to those of experienced designers.

An open question based on the present research is whether the novice designer's unreasoned approach to analogizing also apply to between domain analogies. It may be that novice designers lack the domain knowledge necessary to make reasoned transfers, or alternatively perhaps they lack the skills necessary for making reasoned transfers in general. Future research should thus attempt to clarify whether the novice designers' unreasoned approach to analogizing generalize to their reasoning on between domain analogies also, or whether they are in fact capable of making reasoned analogizing there.

7 CONCLUSIONS

This paper described a study of six novice and six experienced design engineers observed while working in the aerospace industry. It is the first real world data study of expertise level differences in use of analogies and contributes to an understanding of how engineers use and reason about analogies. The research questions in particular looked at the purpose of analogies in a variant design domain; differences in analogical reasoning between novice and experienced designers; and potential differences in analogizing based on the stage of design or the design task at hand.

The research suggested that the variant design domain influenced the distance of the analogies found, with all but one analogy being within domain. The incremental nature of the aerospace domain and complexity involved may explain this. The research presented has shown clear differences in the use of analogies by novice and experienced designers. The novice designers were found to predominantly use the analogy as a 'cognitive safe haven' in the face of situations of uncertainty, i.e. a starting point where the transfer to the current design context was made uncritically and unreasoned, and concerned mainly geometric design information. The experienced designers were found to use analogies for reasoning purposes such as problem solving and problem identification thus transferring knowledge of issues and behaviors of sources to the current context. This knowledge allowed them to adapt analogies and reason qualitatively about past and predicted system behavior and not simply reuse components.

Differences were also found between the stages of the problem solving process for which the analogies were used. Experienced designers used the analogies for all three stages and often combined these: generation, evaluation and analysis of solutions, whereas the novices used the analogies predominantly for generation of solutions. The research contributes to an understanding of how the use of within domain analogies changes with experience and also to an understanding of how and what information from analogies can support the generation, analysis and evaluation of current designs, thereby informing the literature of both analogical transfer and case based reasoning.

ACKNOWLEDGEMENTS

The authors acknowledge the support for this research from the Engineering and Physical Sciences Research Council (EPSRC) and Rolls-Royce Aerospace plc when the original data collection took place. The authors acknowledge the support of the designers who participated on the studies, along with that of Dr Michael Moss (Rolls-Royce Aerospace plc).

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