Understanding Internal Analogies in Engineering Design: Observations from a Protocol Study

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Abstract The objective of this research is to understand the use of internal analogies in the early phases of engineering design. Empirical studies are used to identify the following: type and role of analogies in designing; levels of abstraction of search and transfer of analogies; role of experience of designers on using analogies; and, effect of analogies on quantity and quality of solution space. The following are the important results: analogies from natural and artificial domains are used to develop requirements and solutions in the early phases of engineering design; experience of designers and nature of design problem influence the usage of analogies; analogies are explored and unexplored at different levels of abstraction of the SAPPhIRE model, and; the quantity and quality of solution space depend on the number of analogies used.

Keywords Analogy · Novelty · Variety · SAPPhIRE model · Experience

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1 Introduction

Design-by-analogy is used to produce creative solutions [1–3], in particular to enhance novelty and number of solutions [4, 5]. In designing, analogies aid [6] and inhibit fixation [7]. Design-by-analogy involves the transfer of analogous knowledge from a source domain to a target domain, to solve problems in the target domain. The following types of analogies are identified based on different criteria: domain of analogies: natural or biological and artificial analogies; apparent distance between the target and source domains: close domain and distant domain analogies; representation of analogy: verbal-, image- and video-based [3, 7]. In this paper, another category is identified based on development of analogies: internal and external analogies. An internal analogy is created using only the cognitive abilities of designers, mostly based on past experiences. An external analogy is created using an external source like a book, database, computer-based tool, etc. It could be argued that the external analogies also involve cognitive abilities of the designers; however, these kinds of analogies are created primarily due to the use of the external source. Current research on analogies in designing focuses only on understanding and supporting external analogies. As a precursor, it is important to understand the use of internal analogies. Further, this understanding should be the basis for understanding and supporting external analogies. Therefore, this research focuses on understanding internal analogies in designing.

2 Objective and Research Questions

The objective of this research is to understand the use of internal analogies in the early phases of engineering design. Specifically, the following research questions are posed:

1. What are the purposes and types of analogies used in the early phases of engineering design?
2. At what levels of abstraction are analogies searched for in the target domain, created in the source domain and, implemented in the target domain?
3. What is the role of experience of designers on the use of analogies?
4. What is the effect of analogies on the quantity and quality of solutions developed?

3 Research Methodology

Protocol studies of eight design sessions from earlier research [8, 9] are used to answer the research questions. Each design session consists of a designer, experienced (E1-E4) or novice (N1-N4), solving a design problem (P1 or P2),

Table 1 Design sessions (values available from [9])

	E1, P1	E2, P2	E3, P2	E4, P1	N1, P1	N2, P1	N3, P2	N4, P2
VCS	4.44	3.88	3.75	3	2.42	3.14	4.54	3.69
NCS	3.89	3.13	2.92	2.57	1.58	2.14	4	3.54
VIS	255	85	92	72	89	46	132	109
N_{ideas}	103	38	37	32	43	21	40	39

individually, by following a think-aloud protocol, under laboratory conditions (see Table 1). The objective of P1 is to develop solutions for a machine for making holes in any direction in three dimensions, subject to the following machine constraints: (a) change direction while making a hole; (b) make holes of different sizes; (c) make holes in metal, plastic, or wood; and (d) simple, small and portable. The objective of P2 is to develop solutions for a device to clean utensils subject to the following device constraints: (a) meant for urban middle-class family of maximum 10 members; (b) clean all kinds of utensils like tumbler, dining plate, pressure cooker, mixer-grinder, etc.; (c) clean utensils made of all general kinds of materials like stainless steel, porcelain, glass, plastic and aluminum. Before the commencement of designing, all the designers are instructed to develop requirements and as many solutions as possible. They are also instructed to explain on how solutions are developed, but are not told anything about analogies. The time for designing is unconstrained. The transcriptions and measures of solution space—variety of concept space (VCS), novelty of concept space (NCS), variety of idea space (VIS) and number of ideas (N_{ideas})—of these design sessions, available from [9] (see Table 1), are used for the following: (a) identify the analogies and, determine their domains and levels of abstraction, (b) identify the levels of abstraction in the target domain from which the search for analogies commenced and, (c) identify the levels of abstraction in the target domain at which the analogies are implemented. Since the SAPPhIRE model (see Sect. 4.2) can describe outcomes at several levels of abstraction in the early stages of engineering design, the levels of abstraction in the source and target domains are assessed using this model. To assess the effect of analogies on the solution space, Pearson's correlation, from Microsoft Excel™, is used to correlate novelty of concept space, variety of concept space, variety of idea space and number of ideas, with the number of analogies used to develop that solution space.

4 Literature Survey

In this section the relevant literature is organized according to the following topics.

4.1 Analogies

Several researchers studied the role of analogies in designing. The effect of experience of designers on the use of analogies, at the conceptual and detail design stages, is explored through empirical studies in an aerospace industry in [10]. The impact of the different kinds of representations of triggers on the representation and creative quality of design solutions inspired by those triggers in engineering design is studied in [3]. The effect of timing and similarity of analogies during idea generation is studied in [11]. The effect of the apparent distance between the source and target domains on the solutions developed is assessed in [7]. The effects of using no, biological- and engineering-based analogies in idea-generation are studied using an empirical study in [12].

4.2 SAPPhIRE Model

The *S*tate change, *A*ction, *P*art, *P*henomenon, *I*nput, *OR*gan, *E*ffect (SAPPhIRE) model is developed as a model of causality to explain the working of engineered and biological systems [13]. The model is observed to describe outcomes at several levels of abstraction in the early phases of engineering design [14]. Phenomenon is defined as an interaction between a system and its environment (e.g., displacement of an object over a surface). State change is defined as the change in property of the system due to the interaction (e.g., change in position of the object). Action is defined as the interpretation or high level abstraction of the interaction (e.g., movement of the object). Effect is the principle underlying the interaction (e.g., second equation of motion, $x = u \times t + 0.5 \times a \times t^2$). Input is a physical quantity, which comes from outside the system boundary, required for the interaction (e.g., acceleration on the object). Organ is a set of properties and conditions of the system and its environment, also required for the interaction (e.g., degree of freedom of the object in direction of acceleration, acceleration applied for a finite time, Newtonian properties of the object, etc.). Part is a set of components and interfaces that constitute the system and its environment (e.g., object lying on a surface).

4.3 Novelty and Variety

All the definitions and findings in this section are taken from [9]. A concept is defined as an overall solution which is intended to satisfy most of the identified requirements. An idea at a level of abstraction is defined as a constituent of a concept and is intended to satisfy only some requirements. Variety of a concept in a concept space is defined as a measure of a difference of that concept from the concepts developed earlier in that concept space. Variety of a concept space is defined as the average of the variety of all the concepts in that concept space. Novelty of a concept in a concept space is defined as a measure of the difference of that concept from: (a) concepts developed earlier in the same concept space, and

(b) concepts in the other existing concept spaces that satisfy the same overall function. Novelty of a concept space is the average of the novelty of all the concepts in that concept space. Both, variety and novelty of concept space are found to depend on the number of ideas explored at the different levels of abstraction; higher variety and novelty are observed when ideas at higher levels of abstraction are explored more. Variety of idea space is a measure of the difference of the ideas from each other in that idea space. It is also found that variety of idea space correlates well with the variety of concept space, which in turn correlates well with the novelty of concept space.

5 Results

The following observations are made from the analysis of the transcriptions and are supported with utterances from them. Even though the designers are not told anything about analogies, they are found to be used by both, novice and experienced designers. Since no external support is used during the designing, it could be reasoned that the analogies are based on the past experiences of the designers. This is supported by the utterances of E1: *It is a sort of electro-chemical erosion. I have read it somewhere in some manufacturing technology handbook. If you have a book…I do not remember erosion exactly. It is electrochemical erosion. There are other methods in this but that (electrochemical erosion) can be used. It has many limitations*. Here, the designer uses an analogy of electrochemical erosion for removing material and making a hole, and remembers reading about it. Table 2 shows the list of analogies used in all the design sessions. The fact that designers use analogies without being instructed to use them signifies that in studies involving the use of external analogies from a support, designers may be developing both, internal and external analogies. These analogies need to be distinguished, especially while studying the role of the support and experience of designers, on the use of analogies. It is also seen that solutions and requirements previously developed during the same session are also a source of analogies. This is epitomized by the utterances of E1, *That idea* (*laser*) *triggered the second idea of water jet because I felt laser might be little expensive. Water jet is, I think, a little cheaper and, I know that there is a process, so it was not very difficult correlating these two processes*. E1 develops a solution of water-jet machining by using the analogy of laser-jet, which is developed as a solution earlier.

Designers use analogies from both, natural and artificial domains (see Table 2). This observation is illustrated through the following utterances of E1 and N3 for natural and artificial, respectively. *It* (*tool head*) *can stick to any surface it wants to stick to locally, then why don't it have a have a, you know, lizards can stick upside down because of vacuum sort of, so why don't I use that principle here. I want to stick inside it* (work-piece). *It has some sort of vacuum pads it sticks wherever it wants.* Here, E1 uses the analogy of *vacuum principle of lizards* (natural domain) in the tool head, to enable it to fix itself. *So if we have to do that, why not dip the* *fresh utensil in a solution? This idea I got from Fevicol. When you apply Fevicol on the hand and after it gets dried, it comes out as a layer and we can peel off, comes with dirt or say everything*. N3 uses the analogy of Fevicol, a brand of adhesive, which after coming in contact with the hands, forms a layer after drying and can be easily peeled. This analogy can be used for cleaning utensils—utensils are dipped in a special solution, a layer of the material of the solution is formed on the utensils and the layer with the leftovers can be separated after the use of the utensils. A total of 12 and 36 analogies are used from the natural and artificial domains, respectively. All the designers, except N2, use more analogies from the artificial domain than natural domain. This is because all the designers have engineering or architecture backgrounds, and so their previous experiences are based more on the artificial rather than the natural domain. This signifies that, to exploit the rich and diverse knowledge of nature, designers with non-natural backgrounds need assistance.

It is observed that design problems also affect the use of analogies. All the designers solving problem, P1, use more analogies than those solving problem, P2. A total of 36 (11 natural and 25 artificial) analogies are used while solving P1, while an aggregate of 12 (1 natural and 11 artificial) analogies are used while solving P2 (see Table 2). Design problem, P1, is less conventional than problem, P2, therefore, P1 should be tougher to solve than P2. So, solving P1 should require more analogies than solving P2.

It is seen that analogies are used for developing both, requirements and solutions. Analogies for developing requirements is supported through the utterances of E1, *For example, you consider trees, trees grow in all directions in three dimensions, there is no fixed pattern as such and that's the kind of hole I am trying to achieve. So it is basically, there is an open space and, the branches and leaves are growing in different directions, so material is added into space. So, if I think of this problem in a different direction—it would be similar to adding material in open space and achieving my goal of creating cavity. In space I create the material from zero*. Here E1 uses the analogy of three-dimensional growth in tress to develop the requirement of adding material in space, instead of removing material from a given material. Out of a total of 48 analogies, only 4 are used for developing requirements while the rest are used for developing solutions (see Table 2). It has to be noted that the designers are instructed to only explain how the solutions are developed, not requirements. It is reported in literature that analogies can assist in the following: design problem search, identification, interpretation, elaboration, decomposition, and reformulation; solution refinement, evaluation; and evaluation criteria interpretation [2, 3, 15].

Experienced designers use more analogies than novice designers; on average, experienced and novice designers use 7.5 and 4.5 analogies, respectively (see Table 2). No experienced designer, except E1, uses any analogies from the natural domain, but prefer to use more analogies from the artificial domain. While the experienced designers use more analogies from the artificial domain, the novice designers distribute the analogies between the natural and artificial domains. These findings show that experienced designers need assistance for using analogies from

Table 2 Analogies created by designers and their domains, abstraction levels, purposes and implementation

Designer, problem	Analogy number	Analogy used	Domain	Abst. level	Req / sol	Imp. / unimp.
E1, P1	E1-1	Electrochemical erosion	Artificial	Ph	Sol	Imp
	E1-2	Arms of table lamp	Artificial	P	Sol	Imp
	E1-3	Decorative food items in exhibitions	Artificial	P	Sol	Imp
	E1-4	Beetles and insects	Natural	P	Sol	Imp
	E1-5	Rapid prototyping	Artificial	Ph	Req	Imp
	E1-6	Powder metallurgy	Artificial	Ph	Sol	Imp
	E1-7	Random 3-d growth in trees	Natural	A	Req	Imp
	E1-8	Casting	Artificial	Ph	Sol	Imp
	E1-9	Small creature	Natural	P	Sol	Imp
	E1-10	Light	Artificial	P	Sol	Imp
	E1-11	Cost, feasibility, laser jet	Artificial	P	Sol	Imp
	E1-12	Melting	Artificial	Ph	Sol	Imp
	E1-13	Injecting gadgets	Artificial	P	Sol	Imp
	E1-14	Rain water	Natural	P	Sol	Unimp
	E1-15	Cavities in cake	Artificial	P	Sol	Unimp
	E1-16	Chemical etching in PCBs	Artificial	Ph	Sol	Unimp
	E1-17	Complex shapes of human intestines	Natural	P	Sol	Unimp
	E1-18	Bull dozer	Artificial	P	Sol	Imp
	E1-19	Vacuum principle in legs of lizards	Natural	E	Sol	Imp
	E1-20	Globular creatures	Artificial	P	Sol	Imp
E2, P2	E2-1	Thread of bottle cap	Artificial	P	Sol	Imp
E3, P2	E3-1	Shoe polish	Artificial	P	Sol	Imp
	E3-2	Car wash	Artificial	Ph	Sol	Unimp
	E3-3	Washing toilet	Artificial	Ph	Sol	Imp
E4, P1	E4-1	Laser	Artificial	P	Sol	Imp
	E4-2	Flexible arm of robot	Artificial	P	Sol	Imp
	E4-3	Endoscopy	Artificial	Ph	Sol	Imp
	E4-4	Etching	Artificial	Ph	Sol	Imp
	E4-5	Tunnel digging	Artificial	Ph	Sol	Imp
	E4-6	CD burning	Artificial	Ph	Sol	Imp
N1, P1	N1-1	Drilling a tunnel	Artificial	Ph	Req	Imp
	N1-2	Earthworms	Natural	P	Sol	Imp
	N1-3	Insects	Natural	P	Sol	Unimp
	N1-4	Operating inside a human body using small robots	Artificial	A	Req	Imp
	N1-5	Giant-wheel with buckets attached on its periphery	Artificial	P	Sol	Imp
N2, P1	N2-1	Pneumatic guns and pneumatic actuators	Artificial	P	Sol	Imp

(continued)

Table 2 (continued)

Designer, problem	Analogy number	Analogy used	Domain	Abst. level	Req / sol	Imp. / unimp.
	N2-2	Earthworms and rats	Natural	P	Sol	Imp
	N2-3	Tunnel boring	Artificial	Ph	Sol	Imp
	N2-4	Penetration of roots of plants	Natural	Ph	Sol	Unimp
	N2-5	Growth in plants	Natural	Ph	Sol	Unimp
N3, P2	N3-1	Whirlpool	Artificial	Ph	Sol	Imp
	N3-2	Cats and dogs	Natural	P	Sol	Unimp
	N3-3	Fevicol (adhesive glue)	Artificial	P	Sol	Imp
	N3-4	Processes in beauty parlor	Artificial	Ph	Sol	Unimp
N4, P2	N4-1	Sweeping	Artificial	Ph	Sol	Unimp
	N4-2	Hairbrush	Artificial	P	Sol	Imp
	N4-3	Vacuum cleaners	Artificial	P	Sol	Unimp
	N4-4	Evaporators	Artificial	P	Sol	Unimp

the natural domain, while novice designers need assistance for using analogies from both, natural and artificial domains, to be on par with the experienced designers.

From Table 2 the following are observed. All the designers use analogies at the level of abstraction of *part* and, with the exception of E2, *phenomenon*. Analogies at no other levels of abstraction—*action, state change, input, effect* and *organ*—of the SAPPhIRE model are found to be used with the same intensity. This lack of exploration could be because designers do not understand these levels of abstraction as well as the other levels, to explore them with the same intensity. Another set of empirical studies shows that designers do not explore all the levels of abstraction of the SAPPhIRE model with the same intensity, but explore *part* of the SAPPhIRE model with greater intensity [14], although all the levels of abstraction contribute to variety and novelty [9]. This underlies the need for a support to assist creating analogies at the unexplored levels of abstraction.

Table 3 shows the contents in the target domain and their levels of abstraction with which the analogies in the source domain are searched. All the designers search for analogies at the level of abstraction of *action*. Less searching is done at the levels of abstraction of *phenomenon, organ* and *part*. No search is found at the other levels of abstraction of *state change*, *input* and *effect*. All the designers use analogies which are at the same or lower levels of abstraction than the contents in the target domain with which searching is done (see Tables 2 and 3). In other words, the transfer from the target domain to the source domain is always from a higher to the same or lower level of abstraction. The definition of analogous designs in [1] suggests that the search for analogies can happen at function-, behavior- and structure-levels. In the biomimetic design process in [16], search is performed using functions. In the biomimetic design process in [17], a problem is framed in biological terms, and this is used for searching analogies. Four classes of transfer in biomimetics based on the SAPPhIRE model are reported in [18]: copy parts, transfer organs, transfer attributes, and transfer state change.

Table 3 Search, abstraction level of search and implementation of analogies

Analogy number	What was searched	Abstraction level of search
E1-1	Make hole/remove material	A
E1-2	Flexibility	R
E1-3	Make hole	A
E1-4	Material removal	A
E1-5	Make cavity	A
E1-6	Lay material	A
E1-7	Lay material	A
E1-8	Lay material for metals	A
E1-9	Remove material	A
E1-10	Digging material	Ph
E1-11	Remove material	A
E1-12	Make material soft and remove material	A, A
E1-13	Remove material	A
E1-14	Make cavity	A
E1-15	Make cavity	A
E1-16	Remove material	A
E1-17	Make cavity	A
E1-18	Remove material	A
E1-19	Stick at a desired position	Ph
E1-20	Motion of insects	Ph
E2-1	To grip	A
E3-1	To sprinkle	Ph
E3-2	To clean	A
E3-3	To clean	A
E4-1	Material removal	A
E4-2	Flexibility	R
E4-3	Material cutting, removal, etc	A
E4-4	Material removal	A
E4-5	Material removal	A
E4-6	Material removal	A
N1-1	Drill hole	Ph
N1-2	Drill hole and change direction	Ph, A
N1-3	Remove material; size of hole and tool to make hole	A
N1-4	Drill hole and change direction	Ph, A
N1-5	Expanding and contracting tool diameter	Ph
N2-1	Flexibility and stiffness	R; R
N2-2	Make hole in desired direction	A
N2-3	Make hole in desired direction	A
N2-4	Make hole in desired direction	A
N2-5	Make hole in desired direction	A
N3-1	Relative motion between utensil and fluid in contact	A
N3-2	To clean	A
N3-3	To clean	A

(continued)

Table 3 (continued)

Analogy number	What was searched	Abstraction level of search
N3-4	To clean	A
N4-1	Cleaning	A
N4-2	Scrubber	P
N4-3	Cleaning	A
N4-4	Cleaning	A

Among all the analogies developed by the designers, some of them are not implemented into requirements or solutions in the target domain (see Table 2). For instance, designer, E1, uses an analogy of "cavities in cake" for "make cavity", but the designer finds that this analogy cannot be implemented because the direction of making cavity cannot be controlled for the given materials and so, this analogy is not implemented as a solution. Utterances to support are, *I thought cake, cake is porous and has cavities in random direction, but it is made out of baking process*, *so baking process creates the random cavities*, *I won't be able to bake metal*. In another instance, designer, N2 develops an analogy of "penetration of roots of plants underground" and "growth of plants in direction of sunlight" to make a hole in the desired direction—*I am thinking of the roots of the plants*, *it* (*root*) *penetrates and goes inside*. *But they do not have pre-defined path*. *They go in search of water in the ground*. and *Even the plant grows such that it gets maximum sunlight*. For experienced and novice designers, a total of 5 out of 30 analogies (17 %) and 8 out of 18 analogies (44 %) remain unimplemented. This shows the difficulties that the novice designers face while translating analogies from the source domain to the target domain. This shows that designers, in particular novice designers, need assistance in transferring analogies from the source domain to target domain.

To assess the effect of analogies on the variety and novelty of solutions, the variety and novelty of concept space, variety of idea space and number of ideas, all known from earlier research in [9] (see Table 1), are correlated individually, with the number of analogies, as shown in Table 4. The high correlation values between: (a) variety of idea space and number of analogies and, (b) number of ideas and number of analogies, indicate that the use of the internal analogies has positive effects on the quality and quantity of ideas. However, this positive effect is

Table 4 Correlation values

Correlating variables		Correlation value
Variety of concept space	Number of analogies	0.3201
Novelty of concept space	Number of analogies	0.3234
Variety of idea space	Number of analogies	0.8960
Number of ideas	Number of analogies	0.9067

not translated into concepts, as seen by the correlation values between: (a) variety of concept space and number of analogies and, (b) novelty of concept space and number of analogies. Nonetheless, all the correlation values are positive, which show the positive effect of the use of analogies on the quality and quantity of solutions. Analogies help build associations between the target and source domains, which are different from each other. These associations, not possible without the use of analogies, help develop solutions (ideas and concepts), which are different from the existing solutions including those developed earlier, thus enhancing the chances of variety and novelty.

6 Summary and Conclusions

This research helps understand the use of internal analogies in the early stages of engineering design through existing empirical studies. It is found that analogies from natural and artificial domains are used to develop both requirements and solutions in the early phases of engineering design. The experience of designers and nature of design problems influence the usage of analogies. Analogies are observed to be searched, developed and implemented at a few levels of abstraction of the SAPPhIRE model, while the other levels of abstraction are unexplored. The use of analogies has a positive effect on the variety of concept space, novelty of concept space, variety of idea space and number of developed ideas. This research gives directions for developing an assistance to support the use of analogies in the early phases of engineering design.

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