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AN EMPIRICAL EVALUATION OF NOVELTY-SAPPHIRE RELATIONSHIP

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ABSTRACT

The research shown in this paper is to check whether a framework for designing: GEMS of SAPPhIRE as req-sol, developed earlier, can support in the designing of novel concepts. This is done by asking the questions: (a) Is there a relationship between the constructs of the framework and novelty? (b) If there is a relationship, what is the degree of this relationship? A hypothesis - an increase in the size and variety of ideas used while designing should enhance the variety of concepts produced, leading to an increase in the novelty of the concept space - is developed to explain the relationship between novelty and the constructs. Eight existing observational studies of designing sessions, each involving an individual designer solving a conceptual design problem by following a think aloud protocol are used for the analysis. The hypothesis is verified empirically using the observational studies. Results also show a strong correlation between novelty and the constructs of the framework; correlation value decreases as the abstraction level of the constructs reduces, signifying the importance of using constructs at higher abstraction levels especially for novelty.

1 INTRODUCTION

Designing can be envisaged as a means of creating an improved situation from a current situation. The current market scenario is competitive and it requires continuous efforts from a company to retain or improve its competitive advantage. One way of achieving the desired situation viz., retain or improve the competitive advantage, is by developing creative products. Designing is an essential and vital stage in the development of products. Novelty stands for newness and originality, and is a measure of creativity. Hence, designing novel products can help create a competitive advantage by developing a better market.

The central objective of design research is to support industry by developing knowledge in the form of guidelines, methods or tools, to improve the chances of producing a successful product [1]. An earlier work in [2] proposed a framework for designing as a support for novelty.

The research illustrated in this paper is an attempt to do a preliminary evaluation of the framework developed earlier i.e. to check if the framework can support designing of novel concepts.

The paper has been categorized in the following way: Section 1 gave an introduction, Section 2 reports important findings from literature and identifies research issues to be addressed, Section 3 briefs the underlying hypothesis, Section 4 instructs the research methodology adopted, Section 5 reports results and Section 6 gives a summary of the paper and Section 7 shows directions for future work.

2 LITERATURE SURVEY

The following sections report some significant findings from the literature:

2.1 Novelty

Novelty resembles something not formerly known [3]. It resembles unusualness or unexpectedness [4] and happens when an agent generates an outcome without replicating existing outcome(s) [5]. Novelty is taken as one of the measures of creativity of engineering products in [4, 5, 6].

2.2 Types of Novelty

Creativity is defined with reference to: (a) P-creativity (**P**sychological) and (b) H-creativity (**H**istorical) [7]. P-creativity is defined with respect to the previous ideas of the individual concerned and H-creativity is defined with respect to the whole of human history. H-creativity includes P-creativity because a historically creative idea is new to everybody. Since novelty is a measure of creativity, it could be argued that the definition of H/P-novelty along similar logic should also hold valid. Similar ideology in the definition is also followed in [4], where novelty is defined at different levels: personal, societal and historical. In personal novelty an individual discovers or creates products or ideas that are new according to that individual. In societal novelty, a product or idea is new to all people in a particular society, regardless of whether the product or idea is commonplace in other societies. In historical novelty, a product or idea is the first of its kind in the history of all societies and civilizations. Historical novelty subsumes societal and personal novelty, and societal novelty subsumes personal novelty. In this paper, the focus is on historical novelty, because it includes other types of novelty.

2.3 Importance of Novelty

Increasing competition in the world market has forced companies to look for new ideas to improve quality of products [8]. Creative products might be used to increase the price of products and hence get a larger market share [9]. Without creative problem solving, products will be traditional, without a creative edge, which can cause losses at the market [10]. This emphasizes the importance of novelty in products.

2.4 Physical Laws and Effects

Physical laws and effects (henceforth, referred together as effects) are principles of nature that govern a change [11]. These are important in designing because they help synthesize creative products [12, 13]. However, no empirical testing has been done to prove that the use of effects improves creativity. Effects are primarily discovered by scientists to explain the underlying phenomena, rather than to synthesize products that embody these phenomena [13] and as a result these constructs have not been adequately used in designing. This is verified empirically in [5, 14] using observational studies of designing sessions.

2.5 SAPPhIRE Model of Causality

A model of causality - SAPPhIRE (**S**tate change-**A**ction-**P**art-**Ph**enomenon-**I**nput-o**R**gan-**E**ffect) is developed in [11] to explain the behaviour of natural and engineered systems. The constructs of the model are integrated together from the following approaches: Umeda's Function-Behaviour-State, Hubka's Theory of Technical Systems, Andreasen's Domain Theory and, Yoshioka and Tomiyama's Metamodel, to create a more comprehensive model [11]. The model and definition of its constructs can be seen in Figure 1 and Table 1, respectively. A description of functionality can take different forms: an action description (e.g., cool body, move body, generate current, etc.), input-output of a system (e.g., temperature difference as input to heat transfer as output, acceleration as input to displacement as output, potential difference as input to current as output, etc.) and state changes (e.g., change in temperature, change in spatial location, change in current, etc) [11]. The ability of the model to accommodate functionality in its different forms and link them together provides a greater richness in the description of functionality. Physical phenomena and physical laws/effects together are rarely supported by a single model or approach in the literature. The use of these constructs together and their links with functionality provides a richer description of behaviour. Action, state change and input form the higher levels of abstraction. Physical phenomenon and effect comprise the intermediate levels of abstraction. Organ and part form the lower levels of abstraction. The model of causality can be explained as follows [15] (see Figure 1): A set of components and interfaces that constitutes a system and its environment (parts) creates a set of properties and conditions of the system and its environment (organs). When the system and its environment are not in equilibrium, there is a transfer of a physical variable in the form of material, energy or signal (input) across the system boundary. This physical variable (input) in combination with a particular set of properties and conditions (organs), together activate a principle (effect). Activation of this principle creates an interaction between the system and its environment (phenomenon). The interaction between the system and its environment creates a change in property of the system (state change). The change in property can be interpreted at a higher level of abstraction (action). The capabilities of the model for analysis and synthesis are demonstrated through examples drawn from multiple domains and the following conclusions are drawn in [15]:

(a) The model can support analysis and synthesis.
(b) The model can support analysis and synthesis of multi-disciplinary systems.
(c) The model can support analysis and synthesis of simple and complex systems.
(d) The model supports conceptual and early embodiment phases.

2.6 GEMS OF SAPPhIRE as req-sol - Framework for Design for Novelty

A prescriptive framework for designing – GEMS of SAPPhIRE as req-sol is developed in [2] to support conceptual and early embodiment designing of novel products. The framework integrates activity, outcome and requirement-solution based elements of designing. **G**enerate, **E**valuate, **M**odify and **S**elect (**GEMS**) are used as activity elements. **S**tate change, **A**ction, **P**art, **Ph**enomenon, **I**nput, o**R**gan and **E**ffect (**SAPPhIRE**) are used as outcome elements. Co-evolving requirements and solutions are used as requirement-solution elements. In [14], these elements are identified from across different approaches in the literature and are validated using a different set of existing observational studies of designing sessions. The validation is done to check if these elements are present in a natural way of designing i.e., when designers are not told explicitly to use these elements. The validation revealed that:

(a) All the elements are present in a natural way of designing.
(b) Not all levels of SAPPhIRE, especially phenomena and effects are adequately explored.

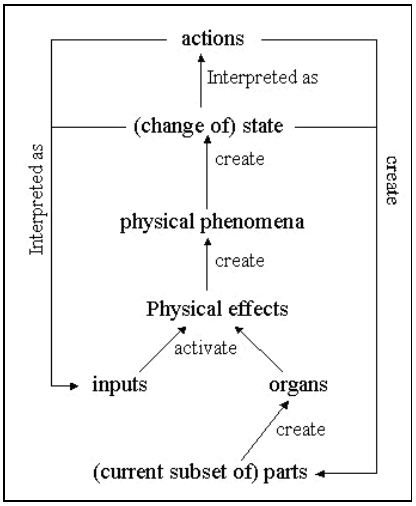

FIGURE 1. SAPPhIRE Model of Causality [11]

TABLE 1. Definition of Constructs [11, 15]

Construct	*Definition*
Phenomenon	An interaction between a system and its environment.
Effect	A principle of nature that underlies/governs an interaction.
Input	A physical variable that crosses the system boundary, and is essential for an interaction between a system and its environment.
State	A property at an instant of time of a system (and environment), that is involved in an interaction.
Action	An abstract description or high-level interpretation of an interaction between a system and its environment
o**R**gan	A set of properties and conditions of a system and its environment required for an interaction between them.
Part	A set of physical components and interfaces that constitute the system and its environment.

One would expect the number of outcomes to increase with decrease in levels of abstraction. This is because an outcome at a higher level of abstraction can be satisfied by multiple alternatives of outcome at the next lower level of abstraction and so forth. The inadequate usage of effects could seriously hamper the chances of designing novel artefacts. The framework is developed to eliminate this drawback. This is achieved in [14] by prescribing designing to be carried out by following GEMS at all the levels of SAPPhIRE for both, requirements and solutions. The framework has two stages: (a) Requirement Synthesis, and (b) Solution Synthesis [2]. In the requirement synthesis, requirements at all the abstraction levels, including SAPPhIRE are generated, evaluated, modified and selected. In the solution synthesis, solutions at different abstraction levels of SAPPhIRE are generated, evaluated, modified and selected. The framework is proposed as a support for designing novel artefacts; however, until now this has not been empirically evaluated.

2.7 Novelty Assessment Methods

Measuring novelty is important because it helps determine a design's newness, patentability, serves as a criterion for comparing designer's capability, helps ascertain a potential market of a product, etc [5]. Novelty is a primary measure of creativity and innovation, whose measurement is useful for research, team recruitment, etc [6].

In [16] the use of experts to identify what is 'creative' is suggested. This is because, ultimately for any measure of creativity to be valid, the results should match the notion held by experts. In [5], the author feels that identification of a novel product in an absolute sense is difficult, since it is difficult to be aware of all the products available in all countries. He proposes that an ideal resource containing information of all products from all domains and their characteristics (e.g. an extensive searchable database) could be a solution to solve this issue. However, in the absence of such an information-base, he believes that novelty assessment could be done by experienced designers who have knowledge of the domain(s) of the product whose novelty is to be assessed.

The research in [17] deals with finding the novelty of patterns restricting primarily to aesthetics and finds novelty through the following questions: (a) How often have similar patterns been experienced? (b) How similar have these patterns been? (c) How recently have the patterns been experienced? Computationally, novelty is detected using processes that estimate these properties for a given stimulus pattern and a representation of previous stimuli. Novelty of a pattern is measured in terms of (a) frequency of similar patterns, (b) similarity of patterns, and (c) similarity in terms of time.

In [4], two approaches are proposed for the measurement of novelty. In the first approach, all the ideas that are non-novel (expected, usual) are collected before analyzing any data. In the second approach, all the ideas produced by the designers are collected. All the key attributes for a design task and different ways by each attribute can be accomplished, are identified. The number of instances of each solution in the entire collection of ideas is counted; lesser this number more is the novelty. The measurement procedure for novelty is as follows. The problem is first decomposed into its key functions or characteristics. Every idea produced is analysed by first identifying what functions it satisfies and describing how it fulfils these functions, at the conceptual and/or embodiment level. Each description is then graded for novelty according to one of the two approaches. A formula to compute a total novelty score for each idea is developed and takes into account the weightage of each function and stage. Apart from measuring novelty, a variety measure is also developed by examining how each function is satisfied. A variety rating of a group of ideas is based on the difference between two ideas from each other. For instance, two ideas are “very different” if they use different physical principles to satisfy the same function and are only “slightly different” if they differ only in some secondary construction level detail.

A method to asses novelty is proposed in [18], based on the following rules: (a) novelty of a product cannot be assessed without assessing its similarity or difference with existing products as reference and (b) several levels of novelty exist due to differences at principle, technology and implementation-levels. The criteria, based on which novelty can be assessed have two levels: vertical and horizontal. Vertical-level criteria are fundamental product characteristics and comprise: need, task, sub-system structure, working principle, technology and implementation. Horizontal-level criteria are based on the relative importance in the overall functioning at that level and comprise: main function, supplementary function(s) and additional function(s). A given product is compared with a reference product and all the differences in horizontal- and vertical-criteria are identified in terms of weightage assigned to each criterion. The novelty value of each difference is computed by multiplying the weightage at that vertical level and horizontal level. This value is multiplied with the horizontal-level weightage at one level above in the vertical direction and multiplication continues until the highest level in vertical direction is reached. The novelty value of each difference is summed up to get the novelty value of the product.

Two methods to measure the novelty of design alternatives are developed in [6]. Each design alternative is classified in terms of its action function, structure and detail. In the first method, novelty is measured in terms of newness with respect to the current paradigm, where each design alternative is classified into one of the four change type patterns: Type 1, Type 2, Type 3 and Type 4 (in ascending order of measure of newness). By counting the relative number of alternatives under each type belonging to each designer or design team involved, novelty of the designer or design team can be assessed. In the second method, novelty is measured in terms of non-obviousness of the outcomes. Non-obvious solutions are those that are produced by few individuals/teams and therefore, the fewer the number of such solutions produced across the individuals or teams concerned, the greater is the non-obviousness. Non-obviousness is measured at different levels, where the number of levels is equal to the number of subjects (team/individual) being compared. For instance, if there are four teams, then the levels are: solutions produced by all four teams, solutions produced by any three teams, solutions produced by any two teams and solutions produced by any one team.

In [5] a method is developed (Figure 3) to assess the qualitative degree of novelty of an engineering product as very high, high, medium or low. The method employs the constructs of FBS and SAPPhIRE together. The method is based on difference in levels of abstraction. If a product whose novelty has to be assessed is different from existing product(s) at a higher level of abstraction then it has a higher novelty and novelty decreases as the difference narrows to lower levels of abstraction. If the product is not different from the existing product(s) then the product is not novel. This method does not use all the constructs of FBS and SAPPhIRE (Behaviour of FBS and Action of SAPPhIRE). The method need not use both FBS and SAPPhIRE because action, state change, and input comprise function, phenomenon and effect comprise behaviour, and organs and part comprise structure. While comparing using SAPPhIRE constructs organ and part, phenomenon and effect, state change and input can be treated separately. This is so because the same organ, phenomenon and state change can be accomplished by multiple alternative parts, effects and inputs, respectively.

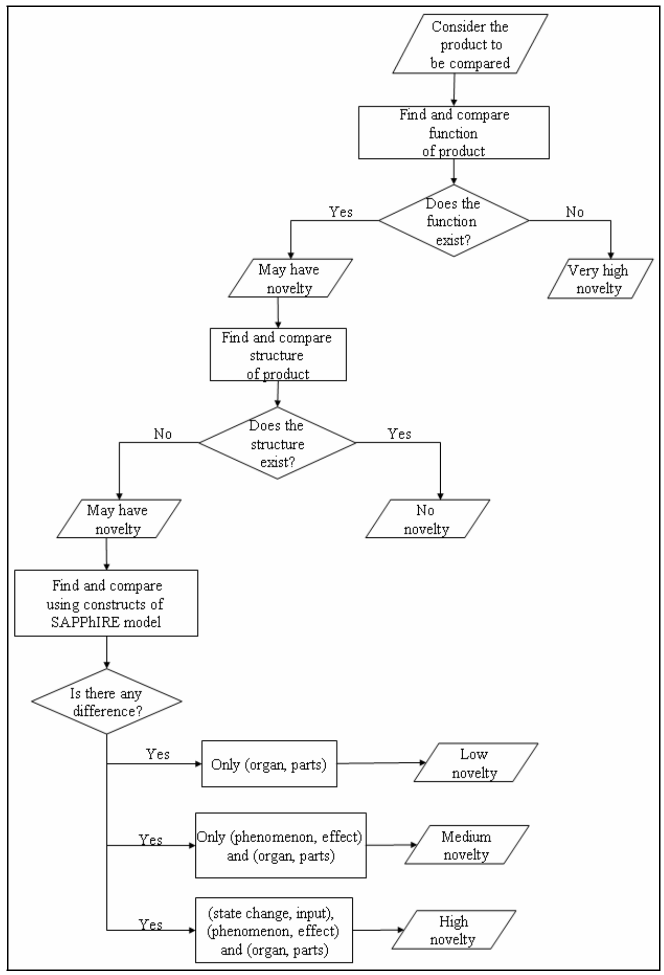

FIGURE 3. Novelty Assessment Method [5]

2.8 SUMMARY

The above sections establish the importance of novelty and of using laws and effects in designing, especially for novelty.

The GEMS of SAPPhIRE as req-sol framework for designing which uses other constructs apart from laws and effects is also proposed to be used to support designing of novel products. However no empirical studies have been done to check the above claims. The focus of this paper is to do an empirical evaluation of the framework by asking the following questions:

(a) Is there a relationship between novelty and the constructs of SAPPhIRE (especially effects)?

(b) If a relationship exists, how strong is the relationship between novelty and the different constructs of SAPPhIRE (especially effects)?

In this research, a modified version of the method proposed in [5] (Annex A.1) is used to assess novelty. This is because it: (a) is capable of linking novelty to various levels of abstraction and (b) uses SAPPhIRE model to link to novelty.

3 UNDERLYING HYPOTHESIS

Before explaining the hypothesis for this study, the terms involved are defined:

Concept: An entity that satisfies an overall function (F). A concept is a solution that satisfies most of the requirements identified for a problem. In Figure 4, C1, C2, C3, and C4 are different concepts that satisfy F.

Idea: An entity at a particular abstraction level that is a constituent of a concept. An idea is a solution that satisfies requirements at a particular abstraction level only. In Figure 4, ideas - a3, b3, and c3 constitute C1.

Idea group: A collection of ideas which are at the same level of abstraction. Each idea group corresponds to a level of abstraction. In Figure 4, ideas a1, a2 and a3 form an idea group called A, ideas b1, b2 and b3 form an idea group called B and so forth.

Size of an idea group (s( )): The number of ideas in that idea group. In Figure 4, s(A)=3, s(B)=3 and s(C)=4

Idea space (IS): A collection of idea groups at all abstraction levels. Each group of an IS forms a level of abstraction and consists of a collection of distinct ideas, all at the same abstraction level. Thus, an IS consists of a collection of distinct ideas at different levels of abstraction. In Figure 6, IS consists of idea groups: A, B and C, which are characterized by their respective levels of abstraction. A, B, and C individually consists of collection of ideas: {a1, a2, a3}, {b1, b2, b3} and {c1, c2, c3, c4} respectively, together constituting the IS.

Concept space: A collection of alternative concepts that satisfy a function.

New concept space (NCS): A set of all concepts produced in a given design process by designer(s), that satisfy the same function. In Figure 4, C1, C2, C3 and C4 satisfy F and constitute the NCS.

Existing concept space (ECS): A collection of all concepts for a given function that existed even before the first concept in NCS was designed. In Figure 4, E1, E2 and E3 constitute the ECS for F.

Variety of a concept (V): A measure of the difference between the concept and all the other concept(s) produced previously in that concept space. For instance, in Figure 4, variety of C4 (shown with dotted lines and double headed solid arrow heads) is represented by comparing it with the previously produced concepts: C1, C2 and C3.

Variety of a concept space (V(CS)): The average of the values of variety of all the concepts in that concept space.

Novelty of a concept (N): A measure of the difference between the concept and: (a) concepts in the ECS that satisfy the same function and (b) concepts(s) previously produced in that concept space. For instance, in Figure 4, novelty of C4 is depicted by comparing it against the existing concepts – E1, E2 and E3 (shown with dotted lines and double oval heads), and concepts previously produced – C1, C2 and C3 (shown with dotted lines and double headed solid arrow heads).

Novelty of a concept space (N(CS)): The average of the values of novelty of all the concepts in that concept space.

Variety of an idea space (V(IS)): A measure of the difference all the ideas from one another in that idea space. In Figure 4, variety of IS (shown with dashed lines and double open-arrow heads) is depicted by comparing all the ideas.

A concept is made of ideas which are at different levels of abstraction (shown by single-headed solid arrow lines in Figure 4). For the same function, the concepts in a new concept space produced by designer(s) are different in terms of the ideas and the combination of ideas used. This contributes to the variety of the concept and the concept space. Since each concept is made of a number of ideas and the variety of each concept is brought out by ideas and combination of ideas used, variety of a concept space depends on the size of the idea groups and the variety of idea space. Variety of idea space also depends on the size of the idea groups. Novelty of a concept depends on the difference of that concept from: (a) concepts in the existing concept space that satisfy the same function and (b) concept(s) designed earlier in that concept space and is also brought out by the ideas and the combination of ideas used. Therefore, it could be argued that novelty of a concept space depends on (a) variety of the concept space and (b) concepts in the existing concept space. However, concepts in the existing concept space cannot be controlled. Therefore, novelty of a concept space depends on the variety of that concept space which is a function of the size and variety of the idea space.

The hypothesis for this study can thus be stated as: An increase in the size and variety of ideas explored while designing should enhance the variety of concepts produced, leading to an increase in the novelty of the concepts.

Each construct of SAPPhIRE corresponds to a level of abstraction and constitutes an idea group of idea space. The use of the framework for designing enables a more detailed exploration of different levels of abstraction (higher size and variety of idea space) which creates variety among concepts in a new concept space, leading to production of novel concepts. So, in a sense the objectives of the paper shown (bulleted points (a) and (b) under Summary Section 2.8) can be realized through the hypothesis. Thus, the objective now reduces to proving the hypothesis.

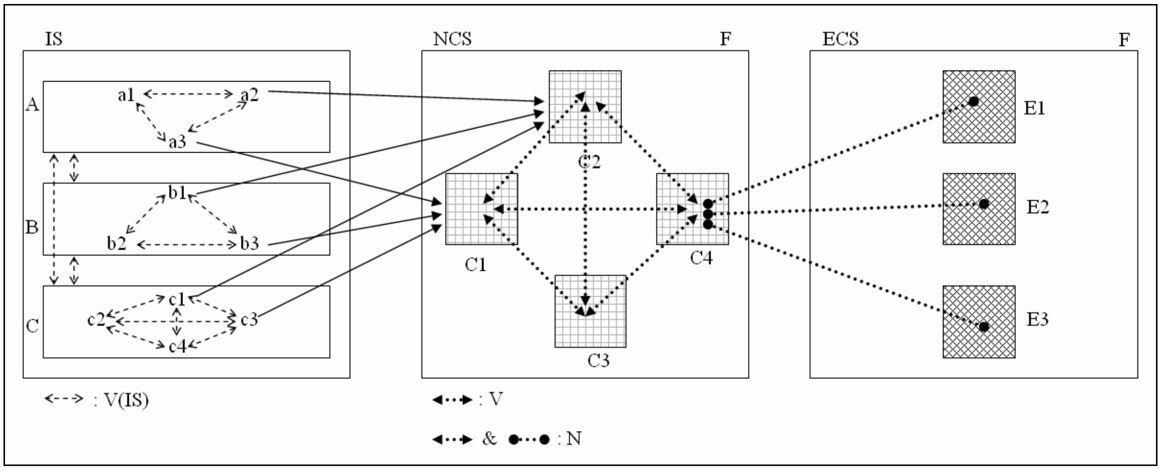

FIGURE 4. Pictorial Representation of IS, NCS, ECS, V and N

4 RESEARCH METHODOLOGY

To empirically achieve the research objectives in the paper through the hypothesis, eight existing observational studies of designing sessions from an earlier research in [5], already available in a transcribed form, are used. Each designing session involves an individual designer, experienced (E1-E4) or novice (N1-N4), solving a design problem (P1/P2) (Table 2) by coming up with conceptual-level solutions following a think aloud protocol in the way shown in Table 3. The experienced designers have atleast two and the novel designers have less than two years of designing experience. No time constraint was enforced on the designers and the problem was solved under laboratory conditions. In each session, the designer was instructed to generate as many concepts as possible, select one of them and detail. The designers were not told about the framework before and while designing.

The following steps are adopted:

Step 1 - Identification of concepts: All concepts produced in each designing session are identified from the transcription.

Step 2 - Identification of ideas: All the ideas that were produced during the session are identified. Not all the ideas that are generated during the session are used in the concepts produced. Ideas are identified by coding the transcription. The ideas are coded (Table 4) according to their level of abstraction into one of the SAPPhIRE constructs.

Step 3 - Estimation of variety of concept: The objectives in this paper require an assessment of the variety of each concept, and accordingly an assignment of a proportionate number. To assess the variety of a concept, a number rating between 1 and 7 (both inclusive) is used corresponding to the seven SAPPhIRE constructs. Here, 7, 6, 5, 4, 3, 2 and 1 correspond to action, state change, input, phenomenon, effect, organ and part, respectively. A value of 0 is assigned if there is no variety (refer Annex section A.1). The following thumb rules are followed while assigning a variety score to a concept:

(i) Irrespective of its nature, the first concept is always given a variety score of 0. This is so because variety requires atleast two concepts.

(ii) The second concept is compared with the first concept to ascertain the ideas that differentiate it from the first. The idea at the highest abstraction level is identified and a variety score is assigned based on the abstraction level of this idea. In this assessment, the idea at the highest abstraction level is considered, because a difference at a higher abstraction level would cause differences at all the subsequent lower levels of abstraction.

(iii) The third concept is compared with the first and the second concept in the concept space to ascertain the ideas, that differentiates it from the first and second. Same procedure is repeated to assess its variety.

(iv) In general, the nth concept is compared with all (n-1) concepts (n>1) generated previously in that concept space to ascertain the ideas that differentiate the nth concept from the others in that concept space. An idea corresponding to the highest level of abstraction is identified from among the ascertained ideas, and a variety score is assigned based on the abstraction level of this idea. This procedure is repeated until all the concepts are assigned a variety score.

Step 4 - Estimation of an existing concept space: An existing concept space is formed by collecting information from internet of products ([19]-[22]) that perform similar or related functions as that given in the problem. It is quite difficult to form an exhaustive collection of existing concepts because there maybe thousands of concepts, that perform the same or similar function. In addition to the above information from the internet, the knowledge of an experienced designer is also used.

Step 5 - Estimation of novelty of a concept: The objectives in this paper require an assessment of novelty, and accordingly an assignment of a proportionate number. To assess novelty of a concept, a number rating between 1 and 7 (both inclusive) is used corresponding to the seven SAPPhIRE constructs. Here, 7, 6, 5, 4, 3, 2 and 1 correspond to action, state change, input, phenomenon, effect, organ and part, respectively. A value of 0 is assigned if there is no novelty (refer Annex section A.1). The following thumb rules are followed in assigning a novelty score to a concept:

(i) The first concept is compared with all the concepts in the ECS to ascertain the ideas that differentiate this concept. In addition, an experienced designer is consulted to cross-verify the ascertained ideas. The idea at the highest abstraction level from among the ascertained ideas is identified and a score is assigned, based on the abstraction level of this idea.

(ii) The second concept is compared with the first concept and all the concepts in the ECS to ascertain the ideas that differentiates this concept. The experienced designer is consulted to cross-verify the ascertained ideas. The idea at the highest abstraction level is identified and a score is assigned based on the abstraction level of this idea.

(iii) In general, the nth concept is compared with all the (n-1) concepts previously produced in that concept space as well as all the concepts in the ECS, to ascertain the ideas that differentiate the nth concept. This is cross-verified with the experienced designer. The idea at the highest abstraction level is identified among the ascertained ideas, and a novelty score is assigned based on the abstraction level of this idea. The procedure is repeated, until all the concepts in the concept space have been assigned a novelty score.

TABLE 2. Problems Solved by Designers

Problem	Description
P1	Design a machine to make holes of any dimension in 3-d, subject to the following constraints: (a) machine should be able to change the direction while the hole is being made, (b) machine should be able to make holes of different sizes, (c) machine should be able to make holes in metal, plastic or wood, (d) machine should be simple, small and portable
P2	Design a device to clean utensils subject to the following constraints: (a) device maybe hand-held or powered (b) device is meant for urban middle class family of maximum size 10 members (c) one should be able to clean all kinds of utensils like tumbler, dining plate, pressure cookers, mixer-grinder, etc. using this device (d) one should be able to clean utensils made of all general kinds of materials like stainless steel, porcelain, glass, plastic and aluminium

Step 6 - Computation of variety and novelty of concept space: The variety and novelty of concept space is computed by averaging the variety and novelty score of all the concepts in that concept space, respectively.

Step 7 - Computation of the size of idea-group: The number of ideas at each level of abstraction is found by counting them individually. As mentioned earlier, not all ideas are used in the concepts by the designers. However, all the ideas produced in each designing session are taken into account.

TABLE 3. Pattern of Problem Solving

	Designer	Problem
Experienced	E1	P1
	E2	P2
	E3	P2
	E4	P1
Novice	N1	P1
	N2	P1
	N3	P2
	N4	P2

TABLE 4. Code for SAPPHIRE

Construct	Code
Action	a
State change	s
Input	i
Phenomenon	ph
Effect	e
Organ	r
Part	p

Step 8 - Computation of variety of idea-space: Variety of an idea-space should take into account the following: (a) variety is always proportional to number of ideas at any level of abstraction, i.e., there is no variety if the number of ideas at an abstraction level is less than 2, and (b) ideas at higher levels of abstraction should account for more variety than the ones at lower levels of abstraction. The following formula is developed based on these propositions:

$$V(IS) = \sum_{j=a}^{p} w_j \left(n_j - 1\right) \qquad (1)$$

n_a, n_s, n_i, n_{ph}, n_e, n_r, n_p: number of ideas at the action, state change, input, phenomenon, effect, organ and part-level

w_a, w_s, w_i, w_{ph}, w_e, w_r, w_p:weightage at the action, state change, input, phenomenon, effect, organ and part-level. The weightages are assigned values: w_a=7, w_s=6, w_i=5, w_{ph}=4, w_e=3, w_r=2 and w_p=1.

Step 9 - Computation of correlation values: In order to determine if there exists any relationship and the degree of relationship between variety/novelty and the different abstraction levels, the following values are correlated:

(i) Variety of concept space – size of idea group at different abstraction levels

(ii) Novelty of concept space – size of idea group at different abstraction levels

To test the hypothesis the following are correlated:

(i) Variety of concept space – Variety of idea space

(ii) Novelty of concept space – Variety of concept space

Pearson's correlation is used to compute the correlation values and it is computed through the in-built function in Microsoft Excel^{TM}. All the correlation values are checked for their level of significance [23] for the given sample size (number of observational studies analysed). Level of significance is a measure of probability that a given correlation value is correct for the analysed sample size..

5 RESULTS

Table 5 shows the number of ideas at different levels of abstraction that is produced in each designing session. In most cases, the number of ideas especially at the state change-, phenomenon-, effect- and organ-levels are very low as compared to the action- and part-levels. Similar results were obtained with the same set of observational studies by researchers in [24] and their objective was to understand the different search spaces explored by designers. The results in Table 5 agree well with the findings in [5] which used another set of observational studies to arrive at similar results. In both these studies the designers were not told about the framework before and while designing, to ensure that the framework was followed by the designers, naturally and spontaneously.

TABLE 5. Number of ideas at different abstraction levels

	Experienced				Novice			
	E1	**E2**	**E3**	**E4**	**N1**	**N2**	**N3**	**N4**
a	9	8	7	6	6	7	13	12
s	1	0	0	1	2	0	0	0
i	1	1	1	2	0	0	0	1
ph	32	7	12	5	9	3	11	7
e	1	0	0	0	0	0	2	0
r	19	2	1	4	1	2	5	1
p	40	20	16	14	25	9	9	18

Table 6 shows the values of variety and novelty of concept space for the eight sessions. Theoretically, value of novelty should be less than that for variety, since novelty accounts for concepts both in the existing and new concept spaces. This trend can be seen for all the eight cases, as shown in Table 6.

Before variety/novelty values are correlated with the size of idea-groups, the idea groups are combined in the following way (Table 7): (a+s+i), (ph+e), and (r+p). This is done for reasons: (a) Designers were allowed to work in a natural way and not instructed about the framework before or while designing and hence there were fewer instances of ideas at s-, i-, e- and r-levels, and (b) a-, s- and i-level ideas together constitute higher-abstraction level ideas, ph- and e-level ideas together constitute medium abstraction-level ideas, and r- and p-level together constitute lower abstraction-level ideas, enabling comparisons between variety/novelty with the size of higher-, medium- and lower-level idea-groups, making the comparison more generic and the results valid in a more wide sense.

TABLE 6. Variety and Novelty of concept space

Designer	V(CS)	N(CS)
E1	4.44	3.89
E2	3.88	3.13
E3	3.75	2.92
E4	3	2.57
N1	2.42	1.58
N2	3.14	2.14
N3	4.54	4
N4	3.69	3.54

TABLE 7. Size of combined idea groups

	s(IS)		
Designer	**s(a+s+i)**	**s(ph+e)**	**s(r+p)**
E1	11	33	59
E2	9	7	22
E3	8	12	17
E4	9	5	18
N1	8	9	26
N2	7	3	11
N3	13	13	14
N4	13	7	19

Table 8 shows the correlation between variety/novelty of concept space with the size of combined idea groups (a+s+i/ph+e/r+p). Note that the number in each cell of this table represents the correlation value between the row and column that connects the cell. The number inside the corresponding bracket represents the level of significance for the sample size (n=8). For instance, 0.66 represents the correlation value between V(SS) and s(a+s+i) and the significance value falls in the range 0.90-0.95. The following observations can be drawn:

(a) Correlation values between variety of a concept space and the size of idea group at the (action, state change and input), (phenomenon and effect) and (organ and part) levels are in descending order, signifying that the variety of a concept space is proportional to the abstraction level of the constructs.

(b) Correlation values between novelty of a concept space and the size of idea group at the (action, state change and input), (phenomenon and effect) and (organ and part) levels are in descending order. This signifies that novelty of a concept space is also proportional to the abstraction level of the constructs.

(c) Variety and novelty are computed using the procedures, explained in Section 4, under Step 3 and 5 respectively. The method used assigns higher variety/novelty scores when constructs at higher abstraction levels are used. The results observed in this section in bulleted points (a) and (b) should not be attributed to the above cause. This is so, because the size of idea groups takes into account ideas that are: (a) used in concepts, as well as those (b) not used in concepts.

(d) The above observations are valid findings because any change in idea/s of a concept at a higher abstraction level has a greater chance of producing a newer concept, i.e., when chances of variety/novelty is higher. This is a result of the fact that a change in a higher abstraction level can potentially cause changes in the all subsequent lower abstraction levels.

Table 9 shows the correlation between variety of concept space - variety of idea space, and novelty of concept space - variety of concept space. The values support the hypothesis i.e. an increase in the variety of ideas explored increases the variety of concepts, which in turn increases the novelty of concepts.

TABLE 8. Correlation value

	V(CS)	N(CS)
s(a+s+i)	0.66 (0.90-0.95)	0.82 (0.98-0.99)
s(ph+e)	0.60 (<0.90)	0.56 (<0.90)
s(r+p)	0.33 (<0.90)	0.33 (<0.90)

TABLE 9. Correlation value to validate hypothesis

	V(CS)
V(IS)	0.65 (0.90-0.95)
N(CS)	0.95 (>0.99)

6 SUMMARY

The section presents a summary of the research in this paper:

(a) The research in this paper is a preliminary evaluation of a framework – GEMS of SAPPhIRE as req-sol, to test whether its constructs have any relationship with novelty. To do this, a hypothesis – an increase in the size and variety of ideas used while designing should enhance the variety of concepts, leading to an increase in the novelty of the concepts – is proposed.

(b) The hypothesis is verified empirically using existing observational studies of designing sessions. In the sessions, designers did not make explicit use of the framework.

(c) The results showed that novelty and variety of a concept space are directly related to the abstraction levels of the outcome constructs. This indicates that there is a greater chance of designing a novel concept, if the higher abstraction levels are explored in greater detail. This inference gains importance especially when designers do not use adequate numbers of laws and effects in their designing, leading to significant potential loss of novelty.

7 FUTURE WORK

Some directions for further work are:

(a) This research is only a preliminary and indirect evaluation of the framework. A more comprehensive evaluation of the framework can be done by comparing concepts produced by designers: (i) Without the framework, and (ii) With the framework.

(b) The framework integrates three elements - activities, outcomes and requirement-solution. This research focuses only on the relationship between novelty and outcomes. However, relationships with novelty could also exist: (a) By performing specific patterns of activities, (b) By identifying specific requirements, and (c) By following definite patterns of requirements and solutions. These relationships need to be investigated.

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ANNEX A.1

METHOD TO ASSESS NOVELTY/VARIETY OF A CONCEPT

The modified version of the method for assessing novelty/variety uses only the constructs of SAPPhIRE and treats each of them separately in decreasing levels of abstraction. First, the actions of the concept are identified and compared with (in the case of novelty assessment, concepts of: existing designs and) concepts produced earlier during the design to check if the actions already exist in these designs. If these actions do not exist, a score for novelty/variety is assigned. If they already exist, then state changes of the concept are identified and compared with those of earlier designs (as before). If these do not exist, then a score for variety/novelty is assigned. If the state changes also exist, then the inputs of the concept are identified and compared as before. If these do not exist, then a score for novelty/variety is assigned. If these also exist, then phenomena of the concept are identified and compared. This method starts by comparing the constructs at the higher levels of abstraction and proceeds in decreasing levels of abstraction – action, state change, input, phenomenon, effect, organ and part. If the parts of the concept already exist in earlier designs, then the concept has no variety/novelty