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AN EMPIRICAL EVALUATION OF A FRAMEWORK FOR DESIGN FOR VARIETY AND NOVELTY

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ABSTRACT
The objective of this paper is to empirically evaluate a framework for designing – GEMS of SAPPhIRE as req-sol – to check if it supports design for variety and novelty. A set of observational studies is designed where three teams of two designers each, solve three different design problems in the following order: without any support, using the framework, and using a combination of the framework and a catalogue. Results from these studies reveal that both variety and novelty of the concept space increases with the use of the framework or the framework and the catalogue. However, the number of concepts developed and amount of time taken to solve the design problem, both decrease with the use of the framework and, the framework and the catalogue. Based on the above results and interview sessions with the designers, an interactive framework for designing to be supported on a computer is proposed as future work.

Keywords: variety, novelty, framework, evaluation, GEMS of SAPPhIRE as req-sol

1 INTRODUCTION
Variety of a concept space is a measure of how concepts within a concept space are different from one another; novelty of a concept space is a measure of how concepts within a concept space are different from one another and from the existing concept space [1]. A framework for designing – GEMS of SAPPhIRE as req-sol – is developed in [2] as a support for design for variety and novelty. The framework integrates activities (**G**enerate, **E**valuate, **M**odify, **S**elect – **GEMS**), outcomes (**S**tate change, **A**ction, **P**arts, **Ph**enomenon, **I**nput, o**R**gans, **E**ffect – **SAPPhIRE**); and **req**uirements and **sol**utions (**req-sol**). The framework provides process knowledge for designing. The framework has not been evaluated to check if it can support design for variety and novelty. A catalogue of physical laws and effects is developed using SAPPhIRE model and provides product-knowledge for designing [3]. Results from [4] show that the use of the framework (process-knowledge) in conjunction with Idea-Inspire [5] (product-knowledge) has potential for supporting design for variety and novelty. However, evaluation using a combined process and product knowledge support in comparison to using only one of these or no support had not been performed. The objective of this paper is to empirically evaluate the influence of the framework, and the framework and the catalogue together, on variety and novelty. An evaluation is carried out to check if there is a difference in variety and novelty of a concept space developed with: no support, the framework, and the framework and the catalogue together.

2 LITERATURE SURVEY
In this section, significant findings from the literature are reported.

2.1 SAPPhIRE model
SAPPhIRE model (see Figure 1 and Table 1) has been developed by Chakrabarti et al. [5] to explain the causality of biological and engineered systems. The model provides a rich description of function (through actions, state changes and inputs), behaviour (through phenomena, effects and organs) and structure (through organs and parts). The model can be used to explain both analysis and synthesis of engineered systems [6]. All the constructs of the model are used naturally by both novice and experienced designers but not all the constructs are explored equally: few phenomena, effects and organs are used [7]. Novelty and variety of a concept space depend on the number of SAPPhIRE outcomes explored at the different levels of abstraction; higher values of variety and novelty are seen if outcomes at higher levels of abstraction are explored more [1].

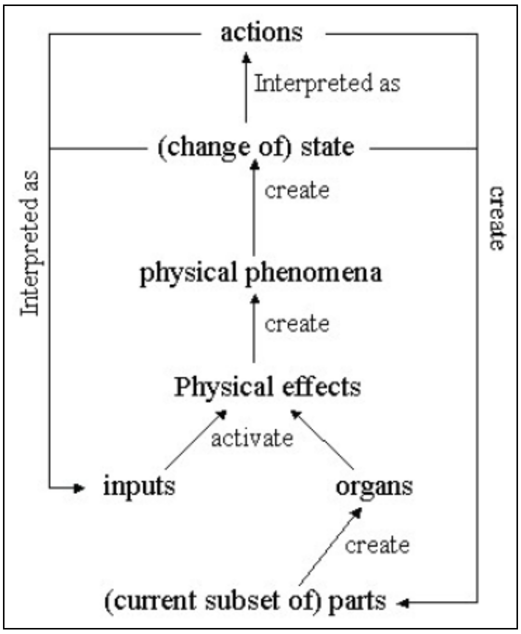

Figure 1. SAPPhIRE model of causality [5]

Table 1: Definition of SAPPhIRE constructs [6]

Construct	Definition
Phenomenon	An interaction between a system and its environment.
State change	A property, of a system or its environment involved in an interaction, which changes during an interaction.
Effect	A principle of nature that governs an interaction, and comprises both physical laws and effects.
Action	An abstract description or high-level interpretation of an interaction.
Input	A physical quantity in the form of material, energy or information, that comes from outside the system boundary and is essential for an interaction.
Organs	The properties and conditions of a system and its environment required for an interaction.
Parts	The physical components and interfaces that constitute a system and its environment.

2.2 GEMS of SAPPhIRE as req-sol: A framework for designing

Existing design theories, models and approaches do not: integrate activities, outcomes, requirements and solutions and make an explicit distinction among them. To resolve this issue, an integrated model of designing – GEMS of SAPPhIRE as req-sol – has been proposed in [7]. This integrated model combines activities (Generate, Evaluate, Modify, Select – GEMS), outcomes (State change, Action, Parts, Phenomenon, Input, oRgans, Effect – SAPPhIRE); and co-evolving requirements and solutions (req-sol). The integrated model is validated in [7] by comparing it against existing protocol studies of design sessions where the model is not explicitly asked to be followed. The validation is done to check if all the constructs of the integrated model are sufficient to describe all instances in designing and vice-versa. Results from this study indicate that all the constructs of the integrated model are naturally used in designing but not all the constructs of SAPPhIRE outcomes are explored adequately. To resolve this, a framework – GEMS of SAPPhIRE as req-sol – is proposed based on the integrated model. The framework provides process-knowledge and prescribes designing to be carried out in two stages: requirements exploration stage (RES) and solutions exploration stage (SES) [2]. In RES, requirements at different levels of abstraction including SAPPhIRE are explored. In SES, solutions at different levels of abstraction of SAPPhIRE are explored in the decreasing levels of abstraction (action, state change, phenomenon, effect, input, organs and parts). A comparison of the framework against existing theories, models and approaches reveals that no existing work combines activities, outcomes, requirements and solutions with explicit distinction among them [8]. However, the framework has not been evaluated empirically to check if it can support design for variety and novelty.

2.3 Catalogue of physical laws and effects

A catalogue of physical laws and effects has been developed using SAPPhIRE model to support design for variety and novelty [3]. The catalogue is intended to provide product knowledge in designing. Each incarnation of a law or an effect in this catalogue can provide: alternative solutions at different levels of abstraction of SAPPhIRE for the same action-level requirement and can also satisfy different action-level requirements. The catalogue has not been evaluated empirically to check if it can support design for variety and novelty.

2.4 Variety and Novelty assessment method

A number of methods have been proposed for assessment of variety and novelty. In this research we use the method proposed in [1] because it is based on the constructs of SAPPhIRE model.
The method for variety assessment is as follows:

(a) A number rating between 1 and 7 (both inclusive) is used corresponding to the seven SAPPhIRE constructs; 7, 6, 5, 4, 3, 2 and 1 correspond to action-, state change-, input-, phenomenon-, effect-, organ- and part-level respectively. A value of 0 is assigned if there is no variety. Irrespective of its nature, the first concept in a concept space is always given a variety score of 0.

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

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

(d) In general, the n^{th} concept is compared with all (n-1) concepts (where n>1) generated previously in that concept space to ascertain the ideas that differentiate the n^{th} 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 level of abstraction of this idea.

(e) This procedure is repeated until all the concepts are assigned a variety score.

(f) The variety of the concept space is the average of the values of variety of all the concepts in that concept space.

The method for novelty is the same as for variety, except that in addition to comparing a concept with all the concepts previously produced in that concept space, one also compares concepts from the existing concept space, i.e., all those existing products that perform the same action. The novelty of concept space is the average of the values of novelty of all the concepts in that concept space.

2.5 Objective

Results from an earlier study in [4] show that a combined use of the framework (process-knowledge) and Idea-Inspire [5] (product-knowledge) has potential for supporting design for variety and novelty. However, evaluation using combined process and product knowledge support in comparison to using only process knowledge support, or using no support at all, has not been carried out before. Thus, the objective of this paper is to empirically evaluate the influence of the framework, and the framework and the catalogue together, on design for variety and novelty.

3 RESEARCH APPROACH

A comparative observational study of design sessions is carried out to validate the framework. Three teams (T1, T2, T3) of two designers each, solve a design problem (P1, P2 or P3) (see Table 2), under laboratory settings. All the teams solve the problems, in the following order: (a) with no support [-F], (b) with the framework [+F] and, (c) with the framework and the catalogue [F+C] (see Table 3). This order is deliberately followed to enable assessment of the impact of the framework and the catalogue, without the chance of the framework and the catalogue affecting the results of the design sessions that were meant to be without any support. All the teams are instructed to follow a think- and discuss-aloud protocol and develop as many conceptual solutions as possible. No time constraints were enforced on

the duration of the design sessions. Each team is asked to develop concepts using a schematic sketch and a brief written-description using the stationery provided. Before the designers solve the first problem, a practice problem is given to train them to think- and discuss-aloud. Tutorial sessions are conducted to train the designers in using the framework and the catalogue. The first three tutorial sessions are conducted between the first and the second design session. The fourth tutorial session is conducted between the second and the third design session. In the first tutorial, the definition of the constructs of activity, outcome, requirement and solution are explained with examples. In the second tutorial, the models of activity, outcome and requirement-solution are demonstrated with examples. This is followed by a doubt-clarification session and a testing session where the designers are tested for their understanding of the constructs, models, and their usage. In the third tutorial, the steps in the framework are explained and demonstrated with the example of the practice problem solved earlier. Further, the designers use the framework to solve the problem which is solved earlier without any support. In the fourth tutorial, the usage of the catalogue is demonstrated using two problems, which have been solved earlier respectively without and with the framework. Two interview sessions are also conducted to understand the pros and cons of the framework and the catalogue, respectively. The first interview session is conducted after the second design session (i.e., after the framework is used); the second session is conducted after the third design session (i.e., after the framework and the catalogue are used). The following specific questions are asked in the interview:
(a) What do you feel about this framework?
(b) Did the framework affect your normal routine of designing?
(c) How difficult or easy was it to use the framework?
(d) Do you want to suggest any directions for improving the framework?
(e) Do you normally use any design methodologies?
(f) What are the broad steps in the methodology that you use?
(g) What do you feel about the catalogue?
(h) Do you feel that the framework with the catalogue was more helpful? In what way was it helpful?

Table 2: Objective of design problems

Problem	Problem Statement
Practice problem	Displacement of objects from one position to another is a common phenomenon. We see people being transported from one position to another, industrial goods getting loaded from one location to another, rocks/stones lifted from different heights, etc. All these applications can be seen as displacing objects from one position to another. Design conceptual-level solutions to displace an object between two locations that are about 5-10 m apart. The object weighs between 1-5 kg.
P1	An obstacle is defined as something that blocks so that any forward movement is prevented or made difficult. Obstacle navigation is one of the widely researched areas in the field of robotics today. It gains prominence especially if a vehicle navigates in territories where the exact topography is unknown. It plays an important role in the safety of the personnel and equipment being carried in the vehicle. Design conceptual-level solutions for obstacle navigation for a vehicle that is to navigate in a rough terrain.
P2	Steering is the act of controlling the direction of a vehicle. It is essential because it enables a user to change the course of the vehicle as desired. Design conceptual-level solutions for steering a vehicle.
P3	Temperature is defined as the degree of hotness or coldness of a system. Design conceptual-level solutions to measure temperature. The design should be able to accommodate as wide a temperature range as possible.

Table 3: Design sessions

	T1	T2	T3
[-F]	P1	P2	P3
[+F]	P2	P3	P1
[F+C]	P3	P1	P2

All the design and interview sessions are video-taped. The design sessions are analysed and the following parameters are computed for each design session:

(a) Variety of concept space (see Section 2.4).
(b) Novelty of concept space (see Section 2.4; existing concept space is taken from [9-16]).
(c) Number of concepts produced.
(d) Time taken to produce all the concepts.
(e) Fluency (ratio of the total number of concepts developed to the time taken to develop these).

4 RESULTS AND DISCUSSION

The parameters – variety of concept space, novelty of concept space, number of concepts, time and fluency – in each design session are analysed for each: (a) problem and (b) team. For instance, variety of concept space is analysed for the three cases with: no support, the framework and, the framework and the catalogue, for each: (a) problem – P1, P2 and P3, and (b) team – T1, T2 and T3. Since each design session involves multiple variables (problem, team, without or with support), an average of each analysed parameter is taken as a representative trend for the parameter.

4.1 Variety of concept space

Figures 2 and 3 show the variety of the concept space for each session, respectively for each problem and team. With the exception of the trend seen for T3 (see Figure 3), all the other trends indicate that the variety of concept space increases by using the framework or, the framework and the catalogue. The average trend shows that the variety of concept space in descending order is: [+F] > [F+C] > [-F].
From the average trend, the variety of concept space *without any support* lies between 2 and 3. This means that variety is primarily through exploration at the organ- and effect-levels (see Section 2.4, bulleted point (a)). The framework, individually and with the catalogue, increases the variety to between 3 and 4. This signifies that variety is through the exploration at phenomenon- and effect-levels. The improvement in variety is due to the *framework*, individually and with the catalogue, to explore constructs that were previously not well-explored without the framework.

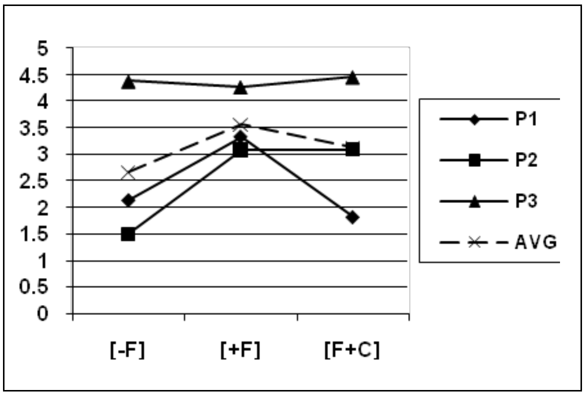

Figure 2. Variety of concept space for problems

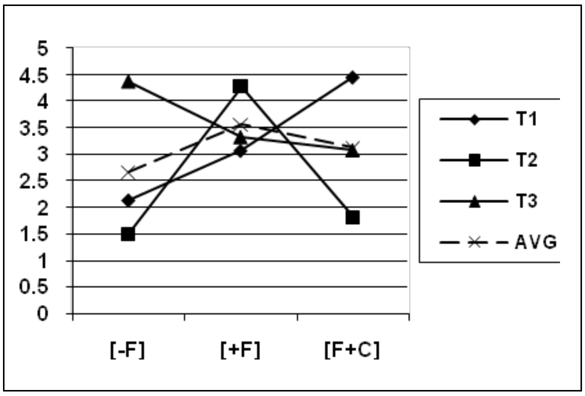

Figure 3. Variety of concept space for teams

4.2 Novelty of concept space

Figures 4 and 5 show the novelty of the concept space for each session, respectively for each problem and team. All the trends here indicate that the novelty of concept space increases by using the framework or, the framework and the catalogue. The average trend shows that the novelty of concept space in descending order is: [+F] > [F+C] > [-F].
From the average trend, the novelty value of the concept space without any support lies between 1 and 2 for the different problems and teams. This shows that novelty *without support* is primarily through exploration at the part- and organ-levels. The framework, individually and with the catalogue, increases this value to around 3. This signifies that novelty is now through the exploration at the effect-level. This increase in novelty is attributed to the *framework*, individually and with the catalogue, that enables exploration of constructs that were not well-explored without the framework.

4.3 Number of concepts

Figures 6 and 7 show the number of concepts produced for each session respectively for each problem and team. All the trends with the exception of T3 (see Figure 7) show that the number of concepts produced is more with the framework or, with the framework and the catalogue. The average trend indicates that the number of concepts is maximum when the framework and the catalogue are used and minimum when no support is used.

The framework, without and with the catalogue, promotes better exploration of more alternatives at each level of abstraction of SAPPhIRE, resulting in more alternative concepts. This is a plausible explanation for the increase in the number of concepts.

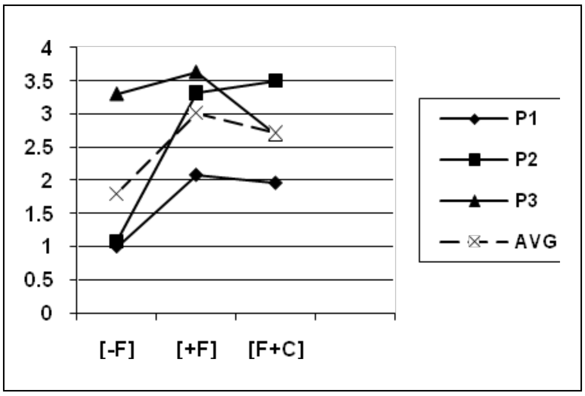

Figure 4. Novelty of concept space for problems

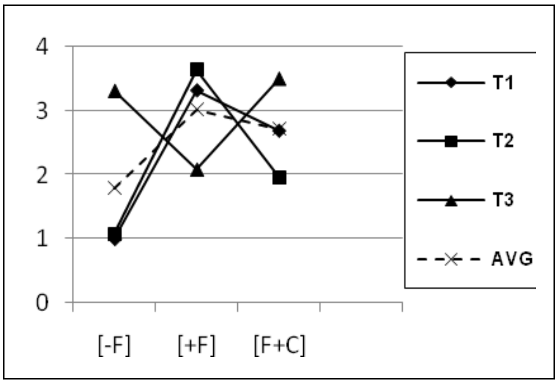

Figure 5. Novelty of concept space for teams

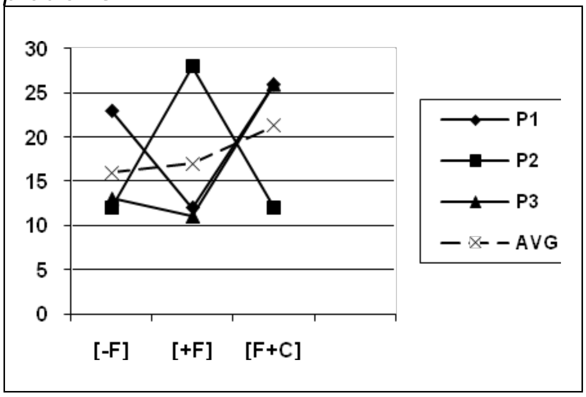

Figure 6: Number of concepts for problems

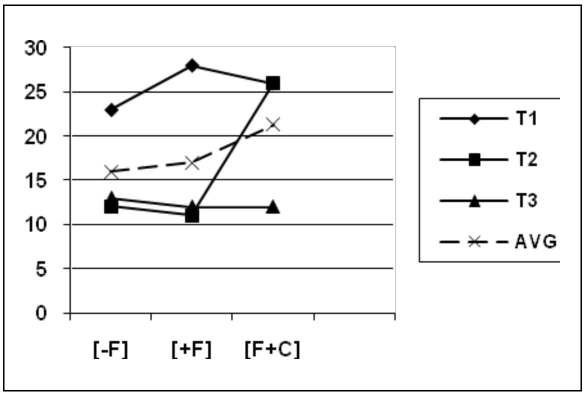

Figure 7: Number of concepts for teams

4.4 Time taken

Figures 8 and 9 show the time taken to produce all the concepts, for each session, respectively for each problem and team. All the trends show that more time is consumed when the framework is used, without or with the catalogue. The average trend indicates that maximum time is consumed when the framework is used and minimum time when no support is used.

The plausible reasons for the observed trend are as follows: (a) exploration of more alternatives at each level of abstraction of SAPPhIRE lead to more alternative concepts, (b) the designers have not used the framework and the catalogue, individually or combined, except during the tutorial sessions. We argue that the framework and the catalogue will be better understood and used with increased usage, and this may shorten the time.

4.5 Fluency

Since the time taken to develop all the concepts and the number of concepts are different for each session, a parameter – fluency, is used for normalisation. Fluency is taken here to be the ratio of the number of concepts produced to the total time taken. Figures 10 and 11 show the fluency, for each session, respectively for each problem and team. Except for the trends seen for P1 and T2, fluency decreases when the framework and, the framework and the catalogue are used. From the average trend, it can be inferred that fluency is maximum when no support is used and least when only the framework is used.

The observed trend is plausibly because the designers have only started using the framework and the catalogue. We argue that the fluency can be improved by increased usage of the framework and the catalogue.

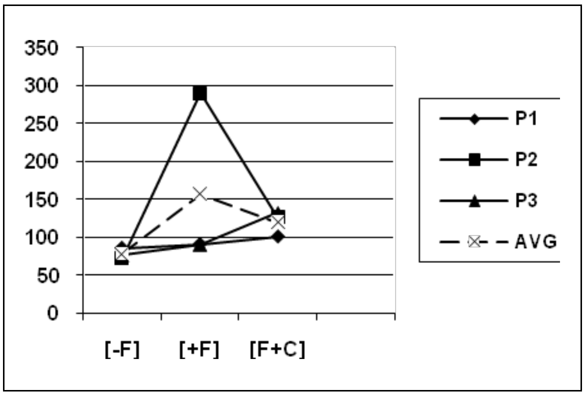

Figure 8: Total time taken for problems

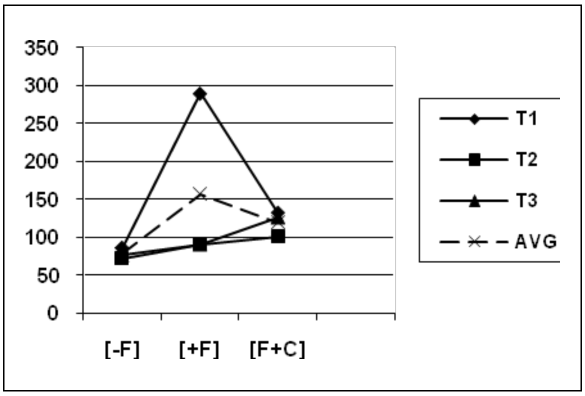

Figure 9: Total time taken by teams

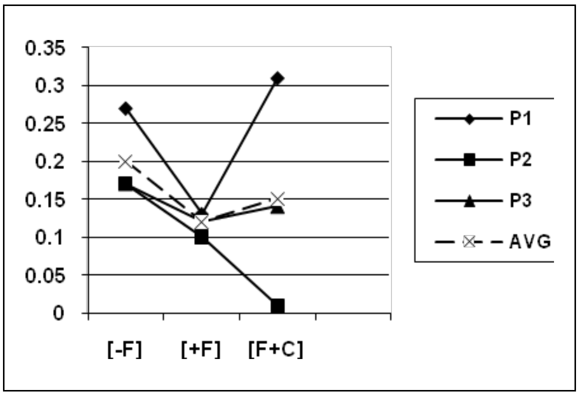

Figure 10: Fluency for problems

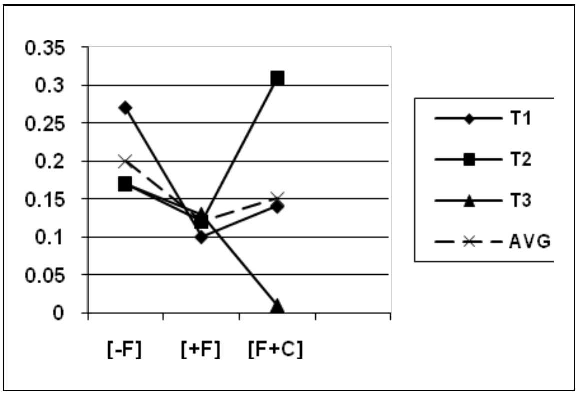

Figure 11: Fluency for teams

4.6 Interview Results

All the observed designers have a Bachelors degree in Mechanical engineering and have less than a year of designing experience. The designers in their limited designing experience have not used any specific design methodology or approach. However, they claim to broadly carry out the following phases: task clarification (including patent and prior-art analysis), concept generation and evaluation, and embodiment. They use methods of brainstorming (individual and group) and morphological charts during concept generation and evaluation. Some designers admit to producing ideas on their own and only then look at the existing set, to check if the ideas already exist. The designers also feel that the kind of methodologies they use are random and rely more on hit-or-miss principles. The responses of these designers are classified below into positives and negatives about the framework and the catalogue:

4.6.1 Positives

T1 feels that the framework helps in diverging and exploring a variety of solutions. This team finds the framework useful because it does not hinder its members' natural creativity and helps in an orderly way of thinking. T2 points out that since the solutions are produced using physics principles, they should be feasible. T2 feels that the framework assists them especially during the initial phase of designing. T3 points out that the framework improves the scope of the team's thinking which is especially useful in the initial phases of designing. The same team feels that the framework helps in a systematic organisation of thoughts thereby reducing randomness.

T1 and T3 feel that the framework is neither very easy nor very tough to comprehend. T1 also expresses that with time and more usage, the understanding of the framework will improve. T2 feels that learning this framework may be helpful.

According to all the teams, using the catalogue with the framework proves useful because the catalogue helps the designers: (a) traverse through the various levels of abstraction of SAPPhIRE, (b) identify new effects, state changes, and organs, and hence new solutions which would not be known otherwise, and (c) recollect some forgotten effects.

T3 likes the idea of having tutorial sessions because its members feel that this is better than reading the literature.

4.6.2 Negatives

T1 and T2 feel that the framework affects their normal routine of designing because they are not habituated in using the framework, and it may take some more time before they get used to them. They also point out that this is true for using any new methodology.

T1 points out that during design, they think in terms of physical and tangible objects. They start to think about part-level solutions while still working at higher levels of abstraction like action and state change. This point is also indicated by T2. T2 feels that the use of effects hinders progress while designing. This at times causes them to switch directly from higher levels of abstraction of action, state change and phenomenon to part, and at other times to force-fitting of the part-level solutions that are conceived earlier. T2 feels that if they do not do this jump, they may not be able to produce enough solutions. T1 indicates that previously they have not used knowledge from basic sciences for designing but worked only at the parts-level. They also add that all the SAPPhIRE constructs except effects and organs can be easily created and changed because knowledge of effects and organs is like a Boolean state – one either knows or does not. T3 conveys that it faces difficulty in understanding organs. This team also feels that the words ‘phenomenon’ and ‘effect’ have a different meaning in English language, which can be a cause for misunderstanding.

T1 points out that the divergence at each level of abstraction can be never ending, and wants to know the end point. T3 feels that the framework is restrictive; more flexibility is required so that their freedom is not lost. T1 argues that in SES, explicit evaluation of solutions against higher-level solutions from which they are generated is sometimes redundant, because generation itself is accompanied by evaluation. T3 makes it explicit that it faces difficulties while trying to categorise requirements into outcome constructs in RES. T1 and T3 feel that the framework is cumbersome.

T1 feels that the current structuring of the catalogue is in contrast to the framework. The framework encourages designers to explore more alternatives at each level of abstraction. On the other hand, each entry in the catalogue shows a complete instance of SAPPhIRE from action to organ-level instead of displaying possible alternatives at each level of abstraction. All the teams feel that the catalogue needs better search facilities.

4.6.3 An Interactive Support

Results from the interview also suggest that the designers face issues while using the framework, individually and with the catalogue. More time is consumed when the designers solve the problems using the framework, without and with the catalogue. This increase in time seems to account for the reduction in fluency. It could be because the framework is not along the natural working mode of the designers and because the designers still face difficulties in using effects and organs. These could be due to the following:

(a) Insufficient tutorial sessions
(b) Rigorousness of the framework
(c) Disruption of the natural working mode of designers
(d) Poor structuring of the catalogue.

To resolve the above issues and to further increase the quality of solutions without compromising on time or fluency, an interactive support that combines both process and product knowledge is planned. In this support, the framework is intended to provide the process knowledge and the catalogue to assist in providing product knowledge. The catalogue is intended to be used at the discretion of the designers, preferably after the designers are exhausted with the concepts developed with their own knowledge. The interactive support is planned to be implemented on a computer platform (see Figure 12). Each cell in the figure shows an activity-outcome combination and, the first and second matrices represent RES and SES respectively. The support should aid two kinds of tasks: computer would either assist the designer, or guide the designer. Different media for assistance are planned: catalogue of physical laws and effects with automated search and retrieval functions to assist in supporting product knowledge; a notebook–interface to enable storage and retrieval of data e.g. for comparison and editing; and a modelling–interface, for simulation and evaluation. Generation of requirements and solutions at all the levels of abstraction of SAPPhIRE will be assisted by the catalogue and the notebook–interface; evaluation of requirements and solutions by notebook– and modelling–interfaces; and, modification and selection of requirements and solutions by the notebook–interface. Guidance will be given under the discretion of the designer, after an activity is completed or when switching between RES and SES. The interactive support should eliminate the need for the tutorial sessions because the computer will guide the designers through the process and provide assistance for product knowledge. The interactive support will also ensure that all the steps of the framework are executed in the order as prescribed.

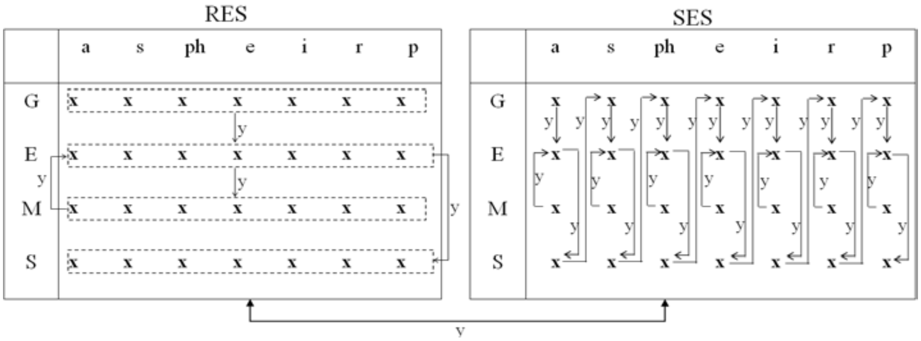

Figure 12. An interactive support (Notation: x-assist; y-guide)[7]

5 CONCLUSIONS

The following conclusions are drawn from the research in this paper:

(i) The variety of concept space increases with the use of the framework, individually or with the catalogue. Thus, the framework, without or with the catalogue, supports design for variety.
(ii) The novelty of concept space also increases with the use of the framework, individually or with the catalogue. Thus, the framework, without or with the catalogue, supports design for novelty.
(iii) The number of concepts developed increases with the use of the framework, individually and with the catalogue. This signifies that the framework and the catalogue encourage better exploration and development of alternatives at each level of abstraction of SAPPhIRE.
(iv) The time taken to produce the concepts also increases with the use of the framework, without and with the catalogue.
(v) The fluency (defined as the ratio of the number of concepts to the time taken) decreases with the use of the framework, without and with the catalogue.
(vi) The interview sessions with the designers suggest that they still face some issues while using the framework and the catalogue, individually and in combination. An interactive support is proposed to alleviate these issues.

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