INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED'07
28 - 31 AUGUST 2007, CITE DES SCIENCES ET DE L'INDUSTRIE, PARIS, FRANCE

UNDERSTANDING SEARCH IN DESIGN

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ABSTRACT
Search and exploration of idea spaces enhances creativity of designers - a necessary ingredient of engineering design. Designers constantly explore and search design spaces to generate or identify solutions. Past research is surveyed in order to explore the current definitions, importance and understanding of the phenomena of search and exploration, and gaps in research in these areas are identified. Next, through design experiments, an in-depth understanding of the process of search and exploration has been sought. Creative efficacy of designers has been studied in relation to the kinds and amounts of search taken place during the design process, leading to the establishment of relationships of creativity with other factors such as experience, search characteristics and time. Finally, guidelines are proposed in order to help designers check their progress towards better designs by controlling the outcomes of the design process proactively during the early design phases.

Keywords: Search, exploration, creativity definition, design

1 INTRODUCTION
Creativity, a major controlling parameter for generating successful products in engineering design, is actualized through search for and of design-spaces. Designers frequently explore and search these design spaces; controlled activation of these search spaces could support enhancement of idea generating capability of engineering designers. It is also important to understand, in depth, how exactly search spaces are explored by designers, from where new ideas come, and what the relationships are among creativity and other parameters of design, such as ability and characteristics of designers and time spent in design.

2 OBJECTIVES AND APPROACH
The work reported in this paper uses empirical studies of designing
(1) To understand the process of idea generation through search and exploration of solution spaces, and
(2) To use this knowledge in order to develop a method (in the form of guidelines) for activation of search spaces to help designers generate creative solutions.

3 LITERATURE REVIEW
Design is the over whelming factor influencing the product life cycle cost and level of innovation. Compared to the overall cost of the entire product development cycle, the design cost is a relatively small part; and yet they have a fundamental bearing on the overall cost, durability, serviceability and utility of the product [1]. Creativity is the essential requirement for product design [2,3] that helps us solve a problem in a satisfactory manner with elegance, unexpected efficiency, or surprising insight [4].

Design is a phenomenon of exploration [5] and search. Exploration or search are similar to idea finding since both are divergent processes, where a lot of ideas need to be considered before selecting the best among them [6]. Also, exploration is an important part of design creativity [7] since creative design is generation and exploration of new search spaces [8]. Exploration also improves designer's problem understanding [5]. Thus, exploration and search should help designers enhance their creativity.

‘Exploration’ is a process by which ill structured knowledge is converted into well structured knowledge through browsing large solution spaces after determining the space within which to search. And ‘search’ is a process of finding improved designs in a given design space. These definitions have been derived from [3, 7, 9-11].

Chakrabarti and Bligh [12] expressed that providing a multitude of possible alternative solutions to a given design problem is a key way to supporting designers, as this would increase their chances of producing the best possible concepts. Gelsey [13] observed that automated search of a space of candidate designs is an attractive way to improve the traditional engineering design process. Stal and George [8] expressed that a dominant problem in engineering design is that generally an optimal design lies out side the search space defined at the start point of the design process. Thus research to understand the process of searching is essential and method for better searching of design spaces is required. Chakrabarti and Bligh [12] mention that designers generally are not able to consider more than a few alternatives without being supported by an enhanced information processing capability. This is because as each design is detailed, the information generated around it grows quickly, making it quite impossible to explore more than but a few alternatives.

4 UNDERSTANDING SEARCH AND EXPLORATION USING DESIGN EXPERIMENTS

4.1 Results from initial design experiments

In the work reported here, an initial analysis was carried out on a set of available protocols (used for research by Chakrabarti [14]), where a set of 8 design experiments, was completed by two groups of designers (three in each group) using four different design methods viz. brainstorming, ideal design, functional analysis and Innovation situation questionnaire.

All the design experiments had been video taped and transcribed. In this project, protocol from each experiment is categorized into three phases: (i) the problem understanding phase, (ii) the idea generation phase and (iii) the evaluation and selection phase. Each utterance made by the designers is separated and listed. Next, these statements are grouped according to their similarity in meaning. Next, these clusters are compared to each other.

First, these protocols are classified into search and exploration. We found that the number of utterances of the type ‘exploration’ is negligible (less than 1 % in all protocols - see discussion later). Next, we observed that searches in the idea generation phase can be further classified into other sub categories according to the link of an utterance with the previous utterances viz. ‘unknown solution search’, ‘global solution search’, ‘local solution search’ and ‘detail solution search’, see Appendix 1 for ways of finding them. It was also observed that similar kinds of search are present only in solution generation, but also in problem understanding and solution evaluation stages.

An ‘unknown’ or ‘global search’ represents search in a global solution space that is less specific than that of the local and detailed spaces (see Appendix. 1). Also, the designers search first unknown or global, then local and ultimately detailed spaces, leading to the solutions getting more and more detailed. ‘Global’, ‘local’ and ‘detailed’ search spaces are previously visited by designers (while solving other similar problems), while ‘unknown’ spaces are not. Search at the higher level in the hierarchy (such as ‘unknown’ and ‘global’) include searches that are in the lower level of hierarchy (e.g., ‘local’ or ‘detailed’). Each of these searches is either on finding potential problems, solutions or evaluation criteria. For instance, a ‘global problem search’ might contain many ‘local problem searches’ and ‘detailed problem searches’, leading to identification of several potential problems at various levels of detail.

It was also found that the designers in general searched for solutions from other previously solved problem situations, and tried to use these directly for the current problem. If this was impossible, modification of the solutions was carried out. Designers repeatedly and spontaneously carried out this ‘search and modify’ process for the entire idea generation phase. Thus, designers often use previous solutions a means for inspiration.

4.2 What is a design space?

Before discussing the results of the main design experiments, we define what we mean by 'design space'. A 'design space' consists of a set of ideas (which can be problems, solutions or evaluating criteria) that are similar to each other in some respect. Depending upon the relationship and level of abstraction used, a design space can overlap with, or subsume other design spaces.

A design space may consist of many problems and their respective solutions. A 'problem space' has many similar problems. Similarly, a 'solution space' has many similar solutions, and an 'evaluation space' has many similar evaluating criteria. 'Solution space' is also known as called 'idea space' (see fig. 1). To access a design space (let us called it 'A'), a designer must be aware of at least one problem and it's corresponding solution belonging to 'A'. Once a designer enters 'A', the designer generally searches for other solutions as well in that space. Theoretically, it is possible for a designer to visit a 'space' which has no relevant solutions. The solution spaces are being described below in some detail (also see Appendix 1).

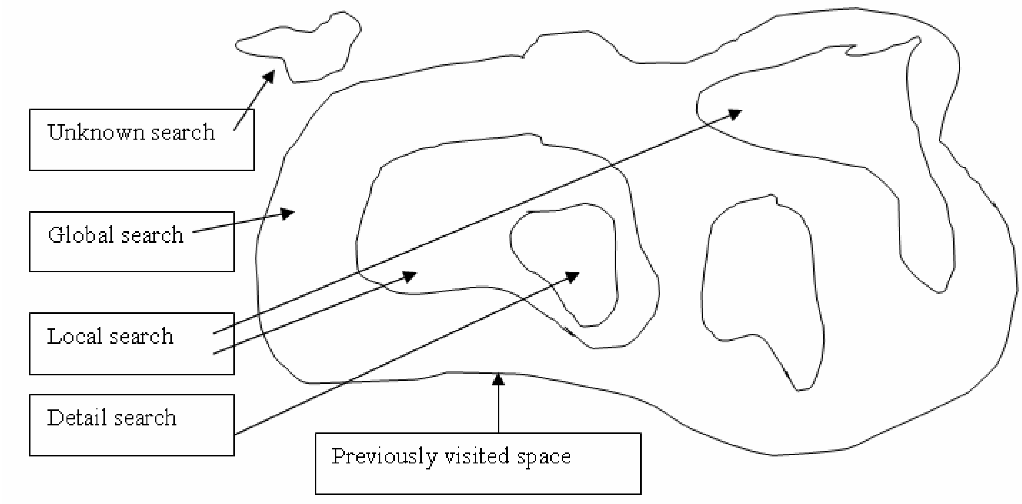

Figure 1. General representation of a 'design space'

4.3 Solution spaces

For a given problem in general, the required functions of all viable solutions are likely to the similar. Basically, the problem calls for activation of a particular set of actions/functions. The behaviour, structure and non contextual/additional functions are different for different ideas.

Solutions are grouped according to their similarity by the researchers. The characteristics of solutions are considered to classify them. Product or idea characteristics can be expressed in many ways, such as technical specifications, feature listing and others, which are specific to the type of product. A general and well documented way of expressing product or idea characteristics is by means of its function, behaviour and structure (FBS). The SAPPhIRE model of causality (see [15]) – a detailed FBS model – was found appropriate for clustering solution related searches (see Appendix 1). The seven elementary constructs of this model are:

1. *Action*: An abstract description or high level interpretation of a change of state, a changed state, or creation of an input.
2. *State*: The attributes and values of attributes that define the properties of a given system at a given instant of time during its operation.
3. *Physical phenomenon*: A set of potential changes associated with a given physical effect for a given organ and inputs.
4. *Physical effect*: The laws of nature governing change.
5. *Organ*: The structural context necessary for a physical effect to be activated.
6. *Input*: The energy, information or material requirements for a physical effect to be activated; interpretation of energy/material parameters of a change of state in the context of an organ.

7. *Parts*: A set of physical components and interfaces constituting the system and its environment of interaction.

4.4 Exploration rarely occurs in design, what occurs is global search

Do designers determine a design space first and then start searching in them? Design experiments do not indicate this. Designers seem to search for ideas and stumble into a new idea space. Generally, this 'stumble' does not seem to be intentional - they do not consciously jump into these spaces. Let us consider one instance from a design experiment where a designer is trying to generate a solution. The problem is related to the design of a means for cleaning utensils.

"…In ways can be probably leaving at in the sink and then taking out, so leaving at in the sink makes it sort of (manual) without say lots of mechanical assistance, so probably this is not a good candidate leaving it in the sink. So I will probably follow some other things rather than leaving it in the sink. Cleansing, I feel, its a water jet. So that the suitable candidate. Jet is the suitable candidate. What else? How else I can do that? Probably you can have something which can shake it; a shaker kind of thing in the water, for that it will not be able to. What else? What else? What else? What else? So, this idea is also not there, shaker is not, then, water jet, air pressure doesn't work. Because, you know, primarily everything will be greasy and oily, so.... and that requires actually water for it. So, I feel air pressure and shaker kind of things (going) to be portable will not work…"

In the experiments conducted, the designers generally took up a system and then tried to retrofit this to the problem as solution. They did not go intentionally into an idea space and start searching for solutions. If they would have gone into an idea space first and then started to search for solutions the transcript would probably look like this: 'Now let me think for a solution in the domain of hydraulics' or 'let me see if water jet can be a solution' or 'Now let me think about pneumatics'. Thus, our observation indicates that pure exploration does not normally happen during unconstrained problem solving (where no methods encouraging this are enforced).

4.5 Main design experiments

Since each initial experiment involved obligatory use of at least one method, it is possible that these of these methods could influence the kinds of search occurring in each experiment and their relative amount. To ascertain the kinds and amount of different searches taking place in an unconstrained design process, and to propose general conclusions on them, the main design experiments are conducted without prescribing use of any particular method. Analysis of the design process with transcribed data from these design experiments and statistical conclusions are presented in the next section. In the main design experiments (semi-controlled in laboratory setting), two types of problems are given to designers, one requiring a substantial amount of mechanical design knowledge and the other requiring general design ability. Eight individual design experiments are conducted with four novice and four experts, all without any prescribed method.

The inter coder consistency was 88 %, which is assessed using two individual coders having 3 years of transcribing experience. After discussion, the entire code, as coded by the main coder, was accepted by the other two coders.

4.6 Results of the protocol analysis of the main design experiments

The transcribed protocol from each design experiment is analyzed and classified in categories, some of which has been mentioned above (see Appendix. 1 for description of all the categories). The results are as follows (the designers are represented by two appropriate alphabets):

Table1. Relationships

Relationship	Represented by	Dh	Ne	Si	Ch	Bh	Sh	Su	Vi
agreeing	Agree	0	4	6	20	6	8	2	6
disagreeing	Disagree	0	0	0	0	0	0	0	1
clarification	Cla	10	41	24	81	63	15	15	9
method	M cla	7	7	19	2	11	5	1	0

clarification									
total clarification	T cla	17	48	43	83	74	20	16	9
selection	sel	2	0	0	0	0	0	0	0
unknown problem search	up	0	0	0	1	0	1	0	0
global problem search	gp	7	10	2	4	2	3	5	2
local problem search	lp	2	7	2	4	0	2	3	0
Detail problem search	dp	11	27	0	9	6	11	1	1
total	T problem	20	44	4	18	8	17	9	3
Unknown solution search	us	0	1	0	8	2	1	3	0
Global solution search	gs	12	29	4	36	7	12	13	8
Local solution search	ls	4	8	5	14	5	2	6	3
Detail solution search	ds	94	63	34	250	52	51	29	58
total	T solutions	110	101	43	308	66	66	51	69
unknown evaluation search	ue	0	0	0	0	0	0	0	0
Global evaluation search	ge	11	12	3	10	5	1	2	1
Local evaluation search	le	3	6	0	1	1	0	0	0
Detail evaluation search	de	14	10	1	5	4	1	1	2
Total	T evaluations	28	28	4	16	10	2	3	3
exploration	explo								1
Problem (P1, p2)		P2	P2	P1	P1	P1	P1	P2	P2
Creativity rank (4 highest)	C rank	4	3	2	4	1	3	2	2

4.7 Correlation of the results and other observations

Pearson co-relation is used on the data and the results of the correlation are given below.

Table. 3. Correlations (refer Table1)

Sl. No.	**Problem Understanding**		**Solution Generation**		**Solution Evaluation**	
	Relationship	**Correlation**	**Relationship**	**Correlation**	**Relationship**	**Correlation**
1	up-gp	-0.19	us-gs	0.73	ue-ge	Nil
2	gp-lp	0.82	gs-ls	0.86	ge-le	0.84

3	lp-dp	0.76	ls-ds	0.82	le-de	0.81
4	up-(gp+lp+dp)	0.06	us-(gs+ls+ds)	0.84	ue-(ge+le+de)	Nil
5	gp- (lp+dp)	0.86	gs- (ls+ds)	0.78	ge- (le+de)	0.90
6	(up+gp+lp)-dp	0.85	(us+gs+ls)-ds	0.83	(ue+ge+le)-de	0.89

Note: Level of significance of the above correlation: $p<0.1$ for values >0.62, $p<0.05$ for values (0.63-0.70), $p<0.02$ for values (0.71-0.79) and $p<0.01$ for values >0.83

4.7.1 Problem understanding

As the number of unknown problem (up) search was very small (only 2 in total, see Table 1), its relationship with other terms is ignored. From Table 3, it can be concluded that global problem search (gp) influences local problem search (lp) and that in turn influences detailed search (dp). Also global problem search influences both local and detailed searches. Again, detailed problem search is influenced by the presence of all other searches at the higher levels of the hierarchy.

4.7.2 Solution generation

There are many unknown solution searches (us) (15 in total, see Table 1), that are previously not known to the designers, found in these design experiments. From Table 3, it can be noticed that unknown solution search positively influences global solution search (gs) that in turn influences the occurrence of local solution search (ls), which influences detailed solution search (dp). Presence of unknown solution search influences the amount of searches of all other types of searches. It has also been noticed that the amount of detailed solution search is controlled by the amount of other searches.

4.7.3 Solution evaluation

There was no unknown evaluation search (ue) in any of these experiments. Table 3 shows that global evaluation search (ge) positively influences local evaluation searches (lp), which in turn influences the amount of detailed evaluation search (de). Global evaluation search influences both local evaluation and detailed evaluation search. It can be concluded that detailed evaluation is influenced by the amount of other types of evaluation search carried out in the process.

4.7.4 Cross correlation

To assess cross-correlation among different kinds of searches that took place in the design experiment, total number of search in each outcome (e.g., problem, solution or evaluation) is considered, i.e. the total number of problem search is a sum of all four types of problem search. A similar process is followed for each outcome.

Table. 3. Relationship among total amount of searches (refer Table 1)

Sl. No.	**Relationship**	**Correlation**
1	Problem searches- Solution searches	0.27
2	Solution searches –Evaluation searches	0.39
3	Problem searches –Evaluation searches	0.78
4	(Total clarification + Problem searches) – Solution searches	0.62
5	Clarification (general)-Solution	0.71
6	Method clarification-Solution	0.30

From Table 3, it can be concluded that problem search influences evaluation search. However, no correlation is found between the amounts of problems identified (total number of all problem searches) by designers and the total number of solutions generated (total number of solutions searches). And, this is not what we expected. Past researchers such as Nidamarthi [16] have shown that better problem understanding helps better solution generation in terms of requirement satisfaction. This researcher did not differentiate between clarification (general clarification method and clarification) and problem searches; it is found, however, that the amount of solution search is influenced by the presence of clarifications and problem search. There is a fair correlation between clarification and solution generation; this hints that clarification of a given problem enhances the generation of the number of potential solutions.

4.8 Creativity of the selected solution of each of these design experiment is measured

The creativity of each of the designer is measured using the final outcome of the design experiments. In each design experiment, the designer selected a final solution after evaluating all the concepts that has been generated during the design process. Two groups, each consisting of two experienced designers, assessed the creative outcomes from each design experiment, using the creativity measuring method proposed by Sarkar and Chakrabarti [17]. The novelty and the usefulness of these designs are assessed, and using these data, the creativity is assessed (see Table 1).

Next, the total number of searches carried out in each phase of design (viz. problem understanding, solution generation and solution evaluation) by different designers is correlated with each other. It has been found that irrespective of the creativity rank of the designers the correlation value is very high (0.99). The calculation is very high for all designers. This indicates that generally a design process follows a particular pattern. The pattern found during solution generation is shown in Fig. 3, but similar pattern is also found for problem understanding and solution evaluation.

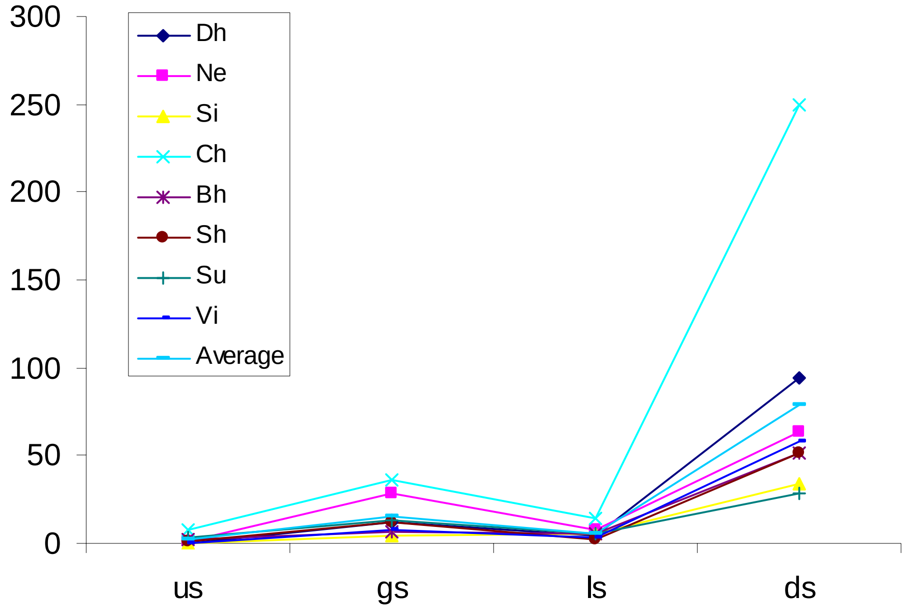

Fig. 3. Pattern found during solution generation

Observations indicate that unknown design spaces are generally less in number, followed by a larger number of global search but comparatively fewer local searches, followed by a huge number of detailed search. We see two potential explanations. In the first, the trend is due to progressive divergence and convergence in the number of search performed, a commonly known means used by designers in order to control the amount of information handled as they go from less to more detailed phases of design [18]. However, this does not explain why convergence has to be at the local search level only.

The second possible explanation is that, once the required design functionality is established, designers work primarily at the device level. This is evidenced by the observation that designers frequently bring to fore past designs and try to mould them to do the current task. This could be due to a lack of knowledge of phenomena and physical principles, and due to the belief that working at the device level is likely to be more pragmatic in terms of creating realistic designs fast.

In the above study, it has also been calculated that on an average:

1. For each unknown problem found, 17 global problems, 10 local problems and 33 detailed problems were generated, and for each global problem, 0.5 local problems and 2 detailed problems were found.

2. A single unknown solution space found was associated with 8 global searches, 3 local searches and 42 detailed searches. Also, each global search led to 0.3 local and 5 detailed searches respectively.
3. There was no unknown evaluation search found. Each global evaluation search led to the generation of 0.2 and 0.8 local and detailed evaluation searches respectively, on an average.

4.9 Duration of the experiment

The effect of the length of the experiment (that is the time spent in designing - 'duration') on designing is assessed by finding its correlation with the presence of different kinds of searches in the design process (see Table 4).

Table 4. Effect of duration of the experiment on searches

Duration –Total number of solutions	0.97
Duration – (Total problem understanding + clarification)	0.69
Duration- Total number of solution evaluation	0.30
Duration - total number of all searches	0.93
Duration- unknown solution searches	0.92
Duration- global solution searches(gs)	0.79
Duration- local solution searches(ls)	0.86
Duration-detailed solution searches(ds)	0.96

Table 4 shows that the duration of the design process increases, this leads to increase in the total number of solutions generated, total number of searches made, total number of problems and clarifications made, as well as to the total number of global, local and detailed solutions generated. Time seems to have less effect on evaluation. Thus as designers spend more time on solving a problem by exploring different kinds of searches, number of potential solutions increases.

4.10 Finding the relationship between different kinds of searches and creative outcome of the individuals

Table 5. Correlation between creativity ranks and searches

Relationship	problem 1	problem 2	Average
Total problem searches - Creativity rank	0.81	0.52	0.67
Total solution searches - Creativity rank	0.77	0.92	0.85
Total evaluation searches - Creativity rank	0.33	0.90	0.62
Time - Creativity rank	0.71	0.87	0.79
Total searches-Creativity rank	0.77	0.85	0.81

Table 5 shows that total number of searches occurring during each phase of design, both individually and all together, influence creativity ranking of the outcome. The Table also shows that, as the amount of time spent for problem solving increases, the creative output also increases. Also, from Table 4 we have seen that as the amount of time spent increases, the amount of searches also increases. This show that time is an important deciding factor for creative design. Even for small design problem solving projects such as these, as the designers spend more time in thinking and generating ideas, the chances are higher that the outcome will be better.

4.11 Correlating experience and KAI

It was noticed here that, the creativity outcome of the experienced designers' were generally higher than that of the novice designers. This probably indicates that experience has a positive effect on the creative outcome of an individual, but given the small sample size this is not a strong conclusion. Interestingly, no high correlation was found between the number of years of experience and the creative outcome for the experienced designers.. More work is required to understand this relationship.

Kirton's Adaptive-Innovative-Inventory (KAI) [18] is administered on all participating designers. It can be noted here that all the designers are innovative. (This finding is not surprising given that the admission procedures for design courses in India are highly competitive, normally students, with highly innovative nature are chosen for these courses). The different in the KAI score among all the designers are not significant. Based of the above understanding, we can create a tentative influence diagram (See Fig. 2).

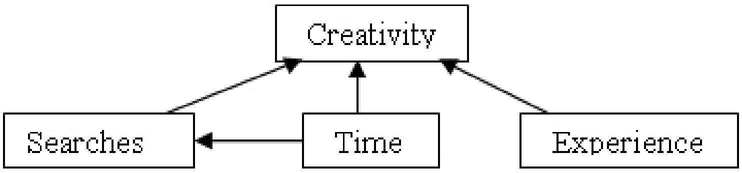

Figure 2. Influence diagram

5 LIMITATIONS OF DESIGNERS FOR EXPLORATION

Generally, not all four different types of search take place in all the three stages. From the design experiments, it is noticed that designers do not explore or search all the design spaces to the maximum possible extent (also observed by Liu et al. [20]). Some possible reasons are:

1. Designers get fatigued.
2. Designers are interested in finding a large number of solutions rather than a 'variety' of solutions.
3. Some designers might not have experience. Experienced designers have already searched the space, so they know the solution clusters in which to search.
4. Problem might be too specific and constrained, thus only detailed searches are possible. Global spaces are generally too huge to search in one sitting and not well structured. It is easy to tell that the detail search is complete or not, since the idea space is smaller and easier to imagine.
5. Designers show loyalty toward project deadlines instead of prioritizing the exploration of new technology or untraditional solutions when time and delivery plans are tight. The problem facing companies and employees in a situation like this is that the pace of innovation is simply not high enough.
6. Designers have mental blocks that restrict the designers to think in divergent ways.
7. Designer's knowledge in multiple engineering fields that might have potential solutions is limited. Often designers are not aware of the existence of potential solutions in a different domain. This is particularly true for novice designers whose repertoire of designs is limited due to lack of experience [12].
8. Designers can be biased toward using certain kinds of solutions, perhaps because they have used them before [12].
9. Designers are more inclined towards generating many solutions rather than variety of solutions, thus they does searching more often rather than exploring [12].

6 GUIDELINES FOR BETTER DESIGN

Observations indicate that generation of solutions occurs in four different levels. We argue that unknown searches and global searches increase the number of uncommon solutions, increasing the variety of the solutions. This increases the chance of getting novel ideas [12]. On the other hand, increase in local searches increases the chances of creating many solutions. Increase in detail search increases the chance of completing the search in that design space. Thus all the four types of searches are important for generating suitable solutions. Also, increase in time of designing enhances both quality and quantity of solutions. So, a designer should do all the four types of searches at a comfortable length of time depending of the difficulty of the problem.

In an ideal design process, the following steps should happen after a problem is given to a designer:
Problem understanding stage

1. Many 'unknown and global problem searches' should be made to identify the major problem characteristics.
2. As many Local problem searches as possible should be carried out in each global problem space developed in the Step 1.
3. Detail problem search should be carried out and requirements generated.

Similarly for solution generation stage and solution selection stage similar searches should take place. From this understanding a guide line has been developed to help designers while designing.

Designers should follow the following guidelines in order to generate a larger number of appropriate solutions.

For Requirement identification

1. Identify the requirements from the problem
2. Identity general requirements (if any) and wishes
3. Cluster the problems into four kinds of searches: unknown, global, local and detail.
4. Give importance to all the four levels of searches equally and try to find as many of them as possible.

For idea and solution generation for a given problem

1. Cluster the solutions according to the four divisions: unknown, global, local and detail search.
2. Now you have a clear idea where the current solutions lack.
3. Give importance to all the four levels of searches equally and try to find as many of them as possible.

For solution evaluation

1. Cluster the evaluating criteria according to the four divisions: unknown, global, local and detail search.
2. Now you have a clear idea where the current solutions lack.
3. Give importance to all the four levels of searches equally and try to find as many of them as possible.

7 CONCLUSIONS

Search is an integral part of design. Searching of design spaces takes places in all phases of design, where designers search these spaces to identify related problems, generate solutions and identify associated evaluating criteria.

Two set of design experiment (initial and main) are analyzed to identify the effect of searching of design spaces on design. It has been found that four types of searches (viz. ‘unknown’, ‘global’, ‘local’ and ‘detail’) take place in all phases of design. These searches influence each other in all phases of design. Occurrence of high level searches in the hierarchy enhances the occurrence of lower level searches. The number of these searches has influence on both the quality and quantity of the design. Design follows a pattern in which these searches occur, and follow a certain trend. Time spent in each phase of design influences the quantity of solutions and creative quality of the solutions. There are some limitations that hinder searching of design spaces. A guideline has been developed that aims to enhance the number in different kinds of searches. The guideline is preliminary evaluated.

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APPENDIX 1: TERMS RELATED TO DESIGN SPACE SEARCH USED IN THE ANALYSIS OF DESIGN EXPERIMENTS

The characteristics of different kinds of searches as shown below:
For the purpose of illustrating let us assume the following given design problem: Design a system that can drill a hole in a material in any direction and whose direction can change while the drilling is in progress.

Solution generation
Unknown solution search (us)

- This occurs when a designer find a new solution, while searching an unknown solution space.
- Not pre-searched, that is the designer did not have any idea about any possible solution of any problem which lies in that space.
- It is characterized by identification of a ‘new function’/ action.
- If the function of the product is compared with that of other products, and this function does not exist in any other product, this is an unknown idea space search.
- Example: ‘Use of 3D laser cutting for soft material.’(that such a technology could be used was ‘unknown’ to the designer)

Global solution search (gs)

- This occurs when a solution is generated thought the search of a global solution space. The designer might have modified the solution after retrieving it from that space. This solution belongs to a new global solution space, i.e., does not belong to any previously visited global solution spaces.
- New idea through search of global search (from global search spaces)
- These searches are recognized by a new solution belonging to a new domain or a change in perspective.

- The new solution is dissimilar from other previous solutions in terms of ‘state change’, ‘input’ ‘Physical Effect’, ‘Physical Phenomenon’, ‘Organ’ and ‘Parts’.
- Example: ‘Use micro robots’ (Robots has been used in manufacturing industry in many countries, but it was a global search for the designer as such an idea was used first time in solving this particular problem. The solution as such is not novel but its use is also the solution is different from previous idea in terms of ‘state change’, ‘input’ and others.)

Local solution search (ls)

- New idea through searching of local search space.
- A local search space is within a global search space; the ideas are similar in terms of input and action, but different in the ‘Physical Effect’, ‘Physical Phenomenon’ ‘Organ’ and ‘Parts’ used.
- Example: ‘Use of remote controlled drilling system’ (here the designer uses new physical effect for this solution. The existing system being standard drilling system).

Detail solution search (ds)

- New idea (or modification of the local idea) through searching in detail, detail search space.
- Solutions in detail search are similar to those in a local search in terms of same state change/action and PP and PE, but are more detailed and it looks as if one has zoomed into the space to have better clarity on a small set of ideas. Difference is only in terms of (Organ and Parts).
- This is identified when there is a change in partial structure, addition of another structure, or modification of the same structure to do other sub-functions.
- Example: ‘…use micro robots that is fitted with a crawler, have laser for cutting and have three stepper motors for three axis movement’ (the designer is detailing a solution that has already been generated earlier).

Problem understanding and problem clarification

Unknown problem search (up): This occurs when a new problem or requirement is found, that was not in any other previous problems or occurs when a designer finds a new problem while searching an unknown problem space.

Global problem search (gp): A new problem found through searching of a global search space and this is characterized by a ‘chronologically’ new problem found by the designer. That is, the problem is searched for the first time while solving this problem. The problem may be not ‘purely’ new, i.e., the problem can be given in the requirement list, the designer may have already had such problems in the past, or problems of such type are already solved by other designers in the past.

Local problem search (lp): The problem is searched within a global search space or some other specific requirements found.

Detail problem search (dp): This has happened if sub-problems are found within a local or global problem space or any expansion, modification of a previous requirement is considered a detail problem search.

Solution evaluation

Unknown evaluation space search (ue): This is characterised by identification of a new evaluation criterion which the designer did not know about before.

Global evaluation space search (ge): This happens when some general evaluation is done, or general evaluation criteria are introduced. The criteria may be already be provided in the problem or developed during problem understanding.

Local evaluation search (le): The evaluation is search within a global evaluation search space.

Detail evaluation search (de): This happens when sub-evaluations are found with a local or global evaluation space, or only a single idea is evaluated in detail.

Other Categories used while coding: Agree and disagree (agrees or disagrees), clarification (clarifying something that a designer does not understand), method clarification (clarifications regarding the method, if any, to be followed in the design experiment) and selection (selection).

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