Towards an 'ideal' approach for concept generation

Y.-C. Liu and *T. Bligh*, Engineering Design Centre, Cambridge University Engineering Department, Trumpington Street, Cambridge CB2 1PZ, UK
A. Chakrabarti, Centre for Product Design and Manufacturing, Indian Institute of Science, Bangalore 560012, India

Conceptual design should contain two kinds of steps: divergent in which alternative concepts are generated, and convergent in which these are evaluated and selected. The aim of conceptual design is to develop promising concepts. This requires generating a wide range of concepts (to prevent overlooking valuable concepts), and evaluating/selecting these soon enough (to restrict their number from getting too large to allow meaningful consideration). Existing concept generation approaches are suggested to be used only after concept sketches are available. This raises a question—what should the 'ideal' approach be before concept sketches are developed? This paper proposes such an approach.

Keywords: Conceptual design, Multiple convergence-divergence, Ideal design approach, Computer supported design, Design methodology

According to creativity and design research [1–4], design activities in conceptual design should contain two kinds of steps—divergent and convergent (see Fig. 1). In a divergent step, a range of concepts is generated, followed by a convergent step in which evaluation and selection of these are made. A principal aim of conceptual design is to generate promising concepts. To achieve this aim, generating a wide range of concepts is important, so that valuable concepts are not overlooked. If designers can develop promising concepts, this should increase the possibility of creating better products [5]. After generating a range of concepts, these should be evaluated and selected at the earliest possible moment, otherwise the number of proposals to consider will continue to grow, making it impossible for designers to consider them meaningfully. Care must be taken here not to discard valuable concepts. A small number of concepts are usually selected for further development.

1 **Guilford J P** Traits of creativity in Anderson, H.H. (Ed.), Creativity and Its Cultivation, Harper & Row (1959) pp 142–161 - reprinted in Vernon, P.E. (ed.) Creativity, Penguin, Harmondsworth (1970).
2 **Pugh, S** Total Design Addison Wesley, Wokingham, UK (1991)
3 **Cross, N** Engineering Design Methods—Strategies for Product Design John Wiley & Sons, Chichester, UK (1994)
4 **Roozenburg, N F M and Eekels, J** Product Design: Fundamentals and Methods Wiley, Chichester, UK (1995)
5 **Chakrabarti, A and Bligh, T P** 'An approach to functional synthesis of design concepts: theory, application, and emerging research issues' *AI EDAMI* Vol 10 (1996) 313–331

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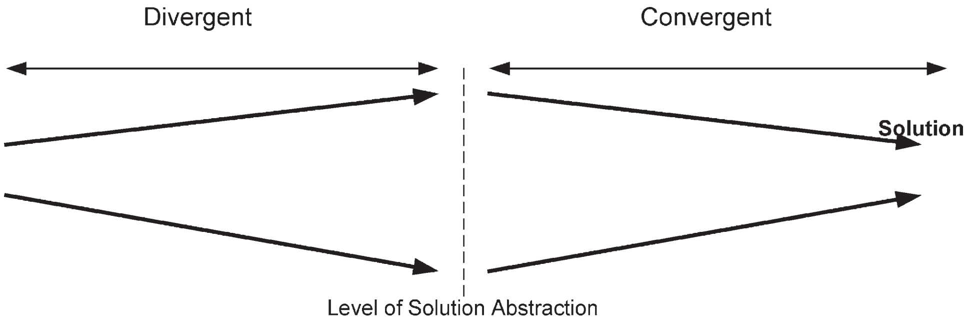


Figure 1 The approach having a single divergent and convergent step.

Various approaches have been suggested for supporting the generation of promising concepts. For instance, Cross [3] characterized the overall design process as being convergent, but maintained that it also contains deliberate divergence for the purpose of widening the search for new ideas (see Fig. 2). The size of the search space after reaching its peak is gradually decreased as the design process continues. Also, Pugh [2] mentioned that it is essential to carry out concept generation[1] and evaluation in a progressive and disciplined manner so as to generate better designs. This progressive and disciplined manner (see Fig. 3) is illustrated as an iterative, repeated divergent and convergent process with the number of solutions gradually decreased. Two common features for the generation of promising concepts are found from Cross and Pugh's prescriptions: (1) the design should follow a multiple divergent and convergent approach; (2) the number of concepts is gradually decreased and only one or few solutions are left at the end of the design stage. However, a problem with their prescriptions is that these approaches are to be followed only after sketches (or visuals)[2] of all concepts have been available. This raises a question—what should the 'ideal' design approach be before sketches of all concepts are generated?

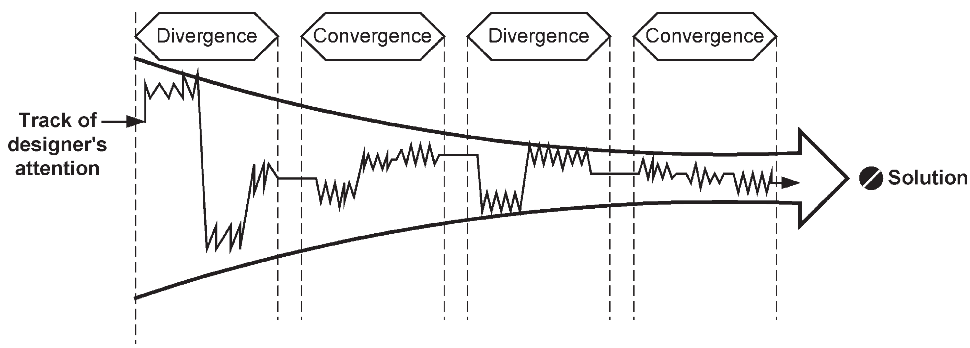


Figure 2 The design approach characterised by Cross (from [3]).

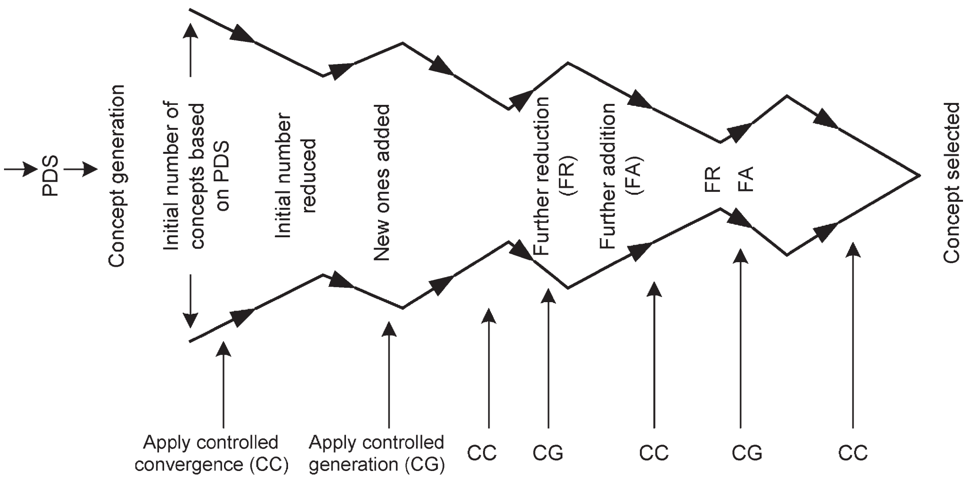


Figure 3 Pugh's model to concept generation and selection (from [2]).

1 An 'ideal' approach: Issues and resulting model

This paper proposes what an ideal design approach should be before sketches are generated. This research is motivated by a functional synthesis approach for combinatorial synthesis and its supporting program, FuncSION [5], the intention of which was to generate a wide range of abstract concepts (more abstract than sketches), so as to solve a class of mechanical design problems involving kinematic movements and their transformation. The idea has been that if designers are provided with these concepts and supported to explore them in detail, this should increase their chances of developing promising concepts, and that in turn would increase the possibility of creating better products. Therefore, a good approach is assumed to be one in which designers are supported and encouraged to generate the widest possible range of concepts, and then to explore, evaluate, and modify these (see, among others, [8–12]). However, the difficulty here is that in practice, designers often consider concepts based on a few principles, and thereby ignore a number of possibilities that are based on other principles. This situation can be improved, if they are presented with a wide range of concepts using computers, in which a wide variety of principles can be considered. However, effective computational tools for concept generation for generic mechanical design are not available. Most approaches to concept generation still rely heavily on the performance of designers. Developing efficient computational tools for concept generation is widely accepted as a principal issue of improving current CAD systems [13].

One of the principal problems found from FuncSION is that while it offered a wide range of alternative concepts for explorations, these were

10 **Adams, J L** Conceptual Blockbusting—A Guide to Better Ideas, 2nd edition W W Norton & Company, New York, USA (1980)
11 **Ullman, D** The Mechanical Design Process McGraw-Hill, New York, USA (1992)
12 **Ulrich, K T and Eppinger, S D** Product Design and Development McGraw-Hill, New York, USA (1995)
13 **Umeda Y and Tomiyama T** Functional reasoning in design IEEE EXPERT (1997) pp 42–48.

too many to be manually explored in a meaningful way. This raises a significant issue: managing the solution space is as important as generating a wide range of concepts. An ideal approach to manage a solution space as well as to generate a wide range of concepts was therefore necessary. This is the focus of this paper.

In order to do this, we need to analyze several alternative divergent-convergent approaches so as to find which provide the best balance between the two conflicting goals of generation of concepts which must go for the widest possible range, and their management which must go for the minimum possible number. A divergent-convergent approach can be characterized by three parameters: (i) the number of levels of abstraction at which divergence/convergence takes place, (ii) the order in which divergence and convergence inter-weave, and (iii) the level at which divergence is at its maximum (i.e. the maximum number of solutions is considered). The analysis, in terms of these parameters, raises the following issues.

(1) Should solutions be synthesised/evaluated in a single step or in several steps to reach the appropriate level of abstraction?
(2) Should the process continue to diverge first and then continue to converge, or alternate between divergence and convergence?
(3) should further divergence be stopped when the solutions are very abstract, very detailed, or somewhere in between?

These three issues are discussed in the next three sub-sections.

1.1 One level vs multiple levels

Here approaches based on a single level or multi-level solution abstraction are compared (see Fig. 4). In principle, design approaches based on one level and multi-level solution abstractions should generate the same number of concepts, if they are based on the same synthesis theory. However, it may be a lot more complex to generate solutions at a detailed level in a single step, rather than in several intermediate steps. In general, one of the principal characteristics of mechanical design is that mechanical products are geometrically coupled. Technical requirements of a machine are achieved by how actual shapes of the machine components interact with each other [11,14]. Based on the requirements, designers generate a few concepts by considering a list of variables including energy flow, three-dimensional form, interface between components, spatial layout of the product, spatial constraint of each component, and the dimension of each component. However, to consider all these simultaneously in order to synthesize all possible concepts is difficult or impossible. Lee et al. [15] addressed that managing complexity is important. One possible way is to consider these variables a few at a time so that the complexity is reduced.

14 Whitney, D 'Why mechanical design cannot be like VLSI design' *Research in Engineering Design* Vol 8 (1996) 125–138
15 Lee C L, Iyenger G and Kota S Automated configuration design of hydraulic systems Proceedings of the Second International Conference on AI in Design, Boston, USA (1992) pp 61–82.

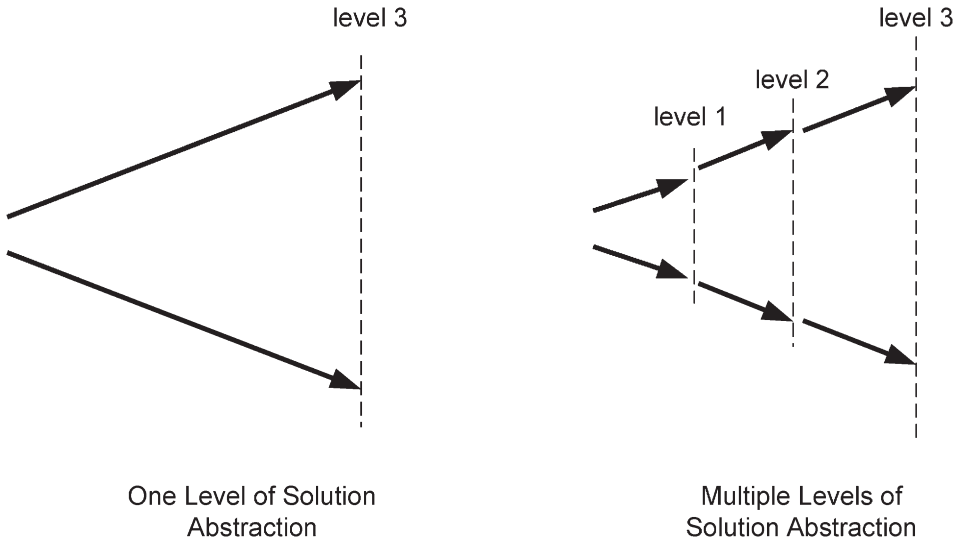


Figure 4 Single vs multiple levels of abstraction.

Having multiple levels of solution abstraction in this respect is better than having a single level of solution abstraction. Complex design problems can be tackled by decomposing them into multiple levels of abstraction. The main challenges here are: (1) what is the abstraction of each solution level with respect to the requirements considered? (2) How are these solution levels related to each other? These two challenges are discussed in Section 4.

1.2 Multiple divergence—multiple convergence vs multiple divergence—convergence

In many cases, transforming solutions from one abstract solution level to the next more detailed level is a synthesis step in itself. This is because when one abstract solution is converted into a more detailed solution, alternative possibilities occur. There are two alternative multiple-level design approaches to concept generation (see Fig. 5). The first is to carry out only synthesis activities at each solution abstraction level until sketches are generated, followed by evaluation and selection of these concepts at the sketch level.

The problem of using a series of divergence without convergence, especially in the context of computational synthesis, using a program such as FuncSION, is that it may lead to a concept space that is too large to explore manually. A number of associated problems may also occur, from the experience of developing FuncSION, such as the generation of *similar* solutions, or solutions which fail to meet other requirements or design

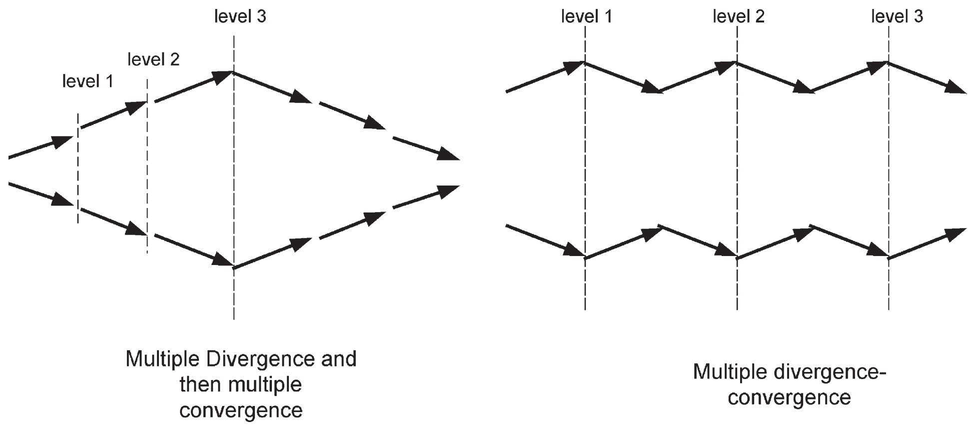


Figure 5 Multiple divergence and then multiple convergence vs multiple divergence-convergence.

constraints not considered directly in solution generation, requiring an unnecessary exploration of these.

The alternative second approach is to carry out divergent and convergent activities in each level of solution abstraction. This should allow a reasonable number of concepts to be generated at each solution level (divergent step), immediately followed by a screening of these concepts (convergent step). By means of these multiple divergent and convergent steps, the management of the solution space can be possible. The challenge here is that solutions represented at an abstract level (e.g. functional level) can be hard for designers to understand. It is a question of how to screen an abstract solution space.

1.3 *The total number of solutions considered*

Since the goal is to consider as many diverse concepts as possible, divergent steps accumulatively increase the number of solutions from the abstract to the detailed solution level. This implies that, ideally, the number of solutions should gradually increase as the solution gets increasingly detailed. However, designers, in practice, are unable to consider all possible solutions [2]. While the generation of concepts is advised, it is also true that these concepts must be reduced at the earliest possible opportunity because in practice, designers cannot consider a great many concepts in detail [9]. The literature suggests that although hundreds of concepts may be found in the concept generation step, only five to 20 will be seriously considered [12]. Therefore, a deliberate decrease of the solution number should be made when solutions are detailed enough to be considered against the major requirements (however, this does not mean that the solutions not developed further are discarded; far from this since it may be required to backtrack to them in more advanced stages when more information is available). This deliberate decrease might happen at various possible levels including the level of abstract concepts, sketches, or detailed designs. If this deliberate decrease is made in the level of abstract concepts, it will not compromise the range of concepts considered; that way, valuable concepts would not be missed. However, evaluation and selection of these abstract concepts will be subjective or even impossible to carry out reliably. Instead, if a deliberate decrease is made at the level of detailed designs (shown in Fig. 6), although the quality for evaluation and selection of these will be better because there are more criteria to be considered, designers in practice would find it difficult to complete the evaluation job because of the very large number of designs to be evaluated.

1.4 An 'ideal' approach

We propose that an 'ideal' approach for conceptual design within a computational framework should follow multiple divergence—convergence in order to gradually increase the number of solutions for the generation of concepts, followed by a divergent and convergent tendency to detail these concepts with an overall decrease in the solution number. This approach is shown in Fig. 7. It is proposed that the maximum number of solutions should be attained at the sketch level since this is the earliest possible level at which designers can meaningfully evaluate them and therefore will provide the widest possible range of concepts to be considered by the designer. If we divide the approach into two parts, the first part enlarges

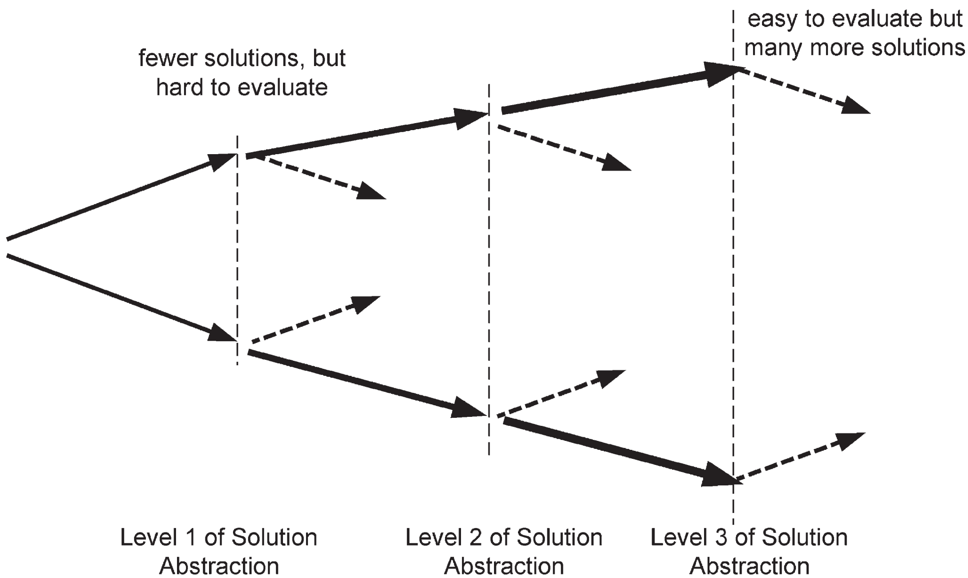


Figure 6 Convergence at abstract vs detailed vs in-between.

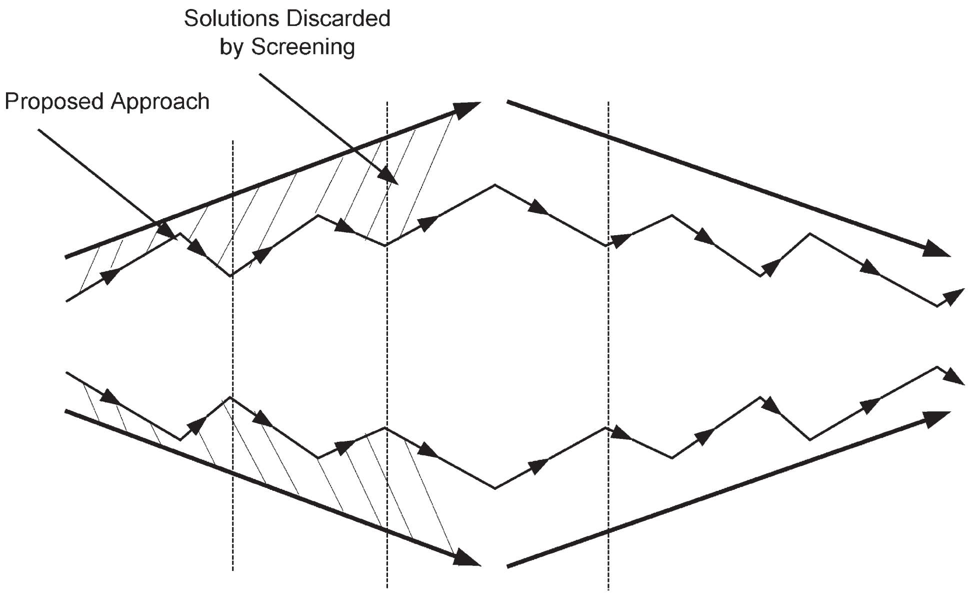


Figure 7 The conventional approach of one divergent–convergent step (dark arrows) and the proposed approach with three divergent–convergent steps.

the overall solution space by divergence–convergence, and the second part reduces it progressively. This second part follows Pugh [2] and Cross's [3] prescriptions, while the first half of the model for the generation of abstract concepts is, on the contrary, to gradually increase the number of solutions. This is done at multiple levels, each of which contains a smaller divergent-convergent step. This approach should be more efficient than a single divergent step, as in FuncSION, because it reduces the number of abstract concepts to be considered by the designer, without compromising on the richness of the space. The next section details the activities of the first part (concept generation) of this approach, in the context of the modified and extended version of FuncSION [16].

2 *Activities for divergence and convergence*

Often designers implicitly discard infeasible solutions based on their experience, particularly at a more abstract level of solutions. However, in developing a CAD tool, the number of concepts can be considerably larger than the number that a designer can manually generate. It is therefore necessary to have a sound approach to control the solution space. Although neither of the approaches suggested by Cross and Pugh address a multiple divergent and convergent approach for the generation of abstract concepts, it seems difficult, based on the experience of developing FuncSION, to manage the solution space without following this.

16 Liu Y C, Chakrabarti A and Bligh T P A computational framework for concept generation and exploration in mechanical design: further developments of FuncSION Proceedings of the Sixth International Conference on AI in Design, Worcester, USA (2000) pp 499–519.

In FuncSION, activities for divergence are to synthesize solutions. Solutions are composed of *building blocks* (see Section 3 for more details on these) stored in a database library. Activities for synthesis involve generating exhaustive variations in these compositions in terms of the number and the types of building blocks composed. Elements (Building blocks) in a solution are connected in accordance with the rules of connection to ensure compatibility.

Activities for convergence are to delete or group solutions based on, respectively, infeasibility or similarity. Solutions can be deleted if they fail to meet further design requirements or constraints. If constraints are subjectively or intuitively provided by designers, it is possible that valuable concepts might be discarded. Some solutions can be grouped together if they are similar. Various types of similarity are identified for this purpose, such as *arrangement similarity* where two solutions are composed of the same building blocks, but in a different order. At a higher abstraction level (such as at the functional level), the infeasibility or similarity between solutions is difficult to assess. Often, these solutions can be assessed only after transforming them into those at a lower abstraction level (such as the physical level). To achieve this without having to detail solutions, a number of simple but powerful heuristics are proposed [17], based on mechanical design experience embedded in physical realizations of abstract solutions.

3 Levels of solution abstraction

Three different but related levels of solution abstraction are currently developed in this methodology, namely topological solution, spatial configuration, and generic physical embodiment level. The descriptions of these three levels of solution abstraction are shown as follows. As an example, the design of a door latch is used here, shown in Fig. 8(c). When the handle is pressed down, it lifts up the wedge, which then moves up as well as to the left, thereby pushing the latch assembly inwards.

- **Topological Solution**: is a combination of a set of pre-defined basic elements, see Fig. 8(a). This is the most abstract solution level in this approach. Basic elements are distilled from observing a wide variety of existing designs that were found to have common elements. Basic elements are classified based on (1) I/O motion (e.g., translation or rotation), (2) I/O directions (e.g., for lever 1 in Fig. 8b, the direction relationship between its I/O is parallel to and non-intersecting to each other) and (3) working principle (e.g. friction, or lever principle).
- **Spatial Configuration**: This is described as a combination of a set of spatial pin elements. Each element is used for the skeletal representation of how the possible embodiment of each basic element is oriented in space. Spatial configuration is an important attribute in most mechanical

17 **Liu Y C** A Methodology for the Generation of Concepts in Mechanical Design Ph.D. thesis, Department of Engineering, University of Cambridge, UK (2000).

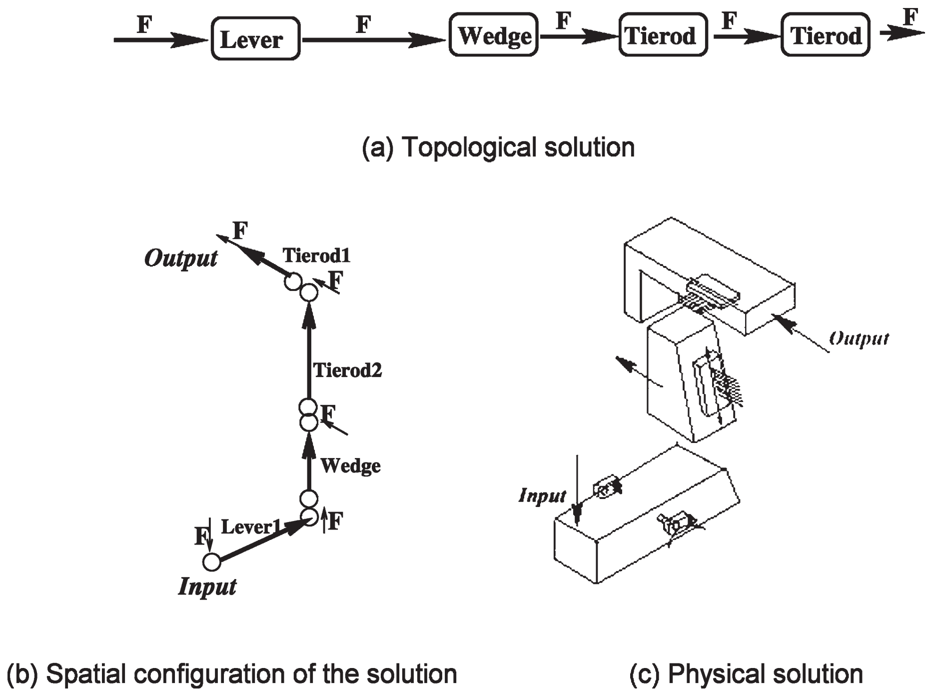


Figure 8 Three levels of representation of a solution.

designs. Solutions at this level provide more information than topological solutions with the aspects of the orientation and position relationships between each element in a solution, see Fig. 8(b). However, shapes, interfaces between elements, and spatial constraints are not represented.

- **Generic Physical Embodiment**: This is composed of a set of generic components or assemblies and their generic interfaces at the geometric level (Fig. 6(c)). Each generic component or assembly has an approximate shape of the real component or assembly. For instance, various forms of a cam along with a specific follower can provide a motion relationship, including first-, second-, and higher-order derivatives. Such cams can all be approximated by the same generic component: a generic cam. Generic physical components or assemblies are represented qualitatively. The connections between components or assemblies, termed motion interfaces, determine the relative kinematic behaviours of the adjoining components. Solutions at this abstraction level provide more information than spatial configurations in terms of qualitative shapes, interfaces, and spatial constraints. This allows designers to visualise the approximate shape of the solutions, and thereby to reason about their kinematic behaviour. However, the exact shapes (such as circle, rectangle, or ellipse) and interface (such as bevel tooth and spur tooth) with their dimensions are not represented.

Fig. 9 is used to illustrate how a pair of spur gears is developed from abstract to detail. Concepts are detailed from topological solutions which are composed of basic elements. Potential spatial configurations for each topological solution are generated, by using all possible spatial variants of each basic element in a topological solution. Based on the spatial configurations, potential physical embodiments are generated exhaustively by using possible generic physical elements of each spatial element in a spatial configuration. The variations at the generic physical embodiment level in terms of the form, support and interfaces are eventually generated. The main difference between these three levels is that topological solutions are generated in terms of a set of labelled basic elements according to the type of energy flow from the input to the output; spatial configurations are represented in terms of three dimensional configurations based on the types and directions of energy flow, as well as on possible components for each element's orientation and position; generic physical embodiments contain geometric forms, interfaces, and spatial constraints. This in future is planned to be extended to further levels of detail, such as the physical embodiment level shown in Fig. 9, which takes into account actual shapes of the components, dimensions, etc.

There are three main features in this implementation of the approach.

- An intermediate representation level, the spatial configuration is used to link between functional and physical levels.

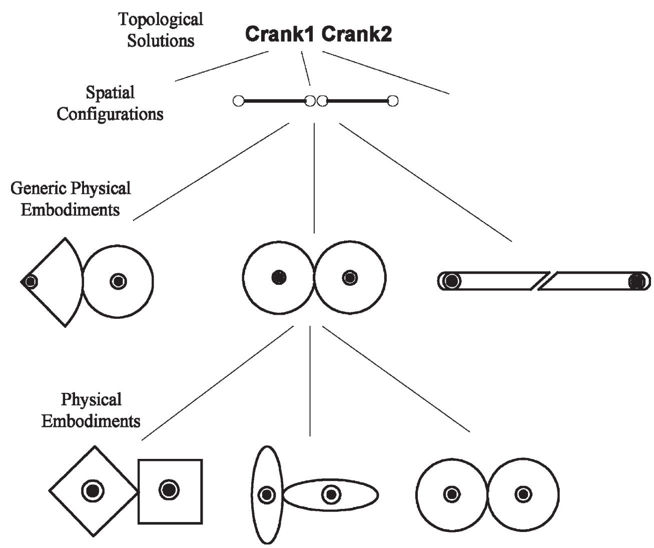


Figure 9 Four solution abstractions for a pair of spur gears[3].

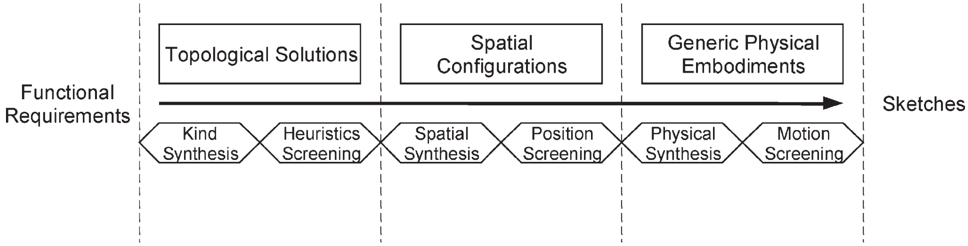


Figure 10 Process of generating concepts in the modified version of FuncSION.

- The interface between elements in the solution at each solution abstraction level is explicitly considered, and is based on rules rather than being implicitly decided by designers.
- The relationships between each solution abstraction level are explicitly defined so that solutions from an abstract level can be computationally generated.

The divergence–convergence process in this implementation is summarised in Fig. 10, which lists the six steps: two at each of the three levels of solution abstraction. The process of expanding the solution space consists of three synthesis processes. The process of narrowing down the solution space involves applying a set of heuristics to discard infeasible solutions or group similar solutions at the topological solution level, another set of heuristics and constraints that can be used at the spatial configuration level, and yet another set of heuristics is at the generic physical embodiment level.

4 *Empirical justification*

This section provides some empirical evidence about the appropriateness of the proposed approach of using a balanced search, and the generic appropriateness of the solution abstraction levels used in the implementation of this approach.

According to Fricke's investigations [19], three tactics were observed during 'solution search', as shown in Fig. 11. They are: (1) Excessive expansion of the search space: solutions are generated and expanded from abstract to detail, without any reduction of the solution number, (2) Balanced search: alternative divergent and convergent search in which the total search space is noticeably reduced as the solutions become more and more concrete, and (3) Unreasonable restriction of the search space: quickly finding a possible solution, without either consciously developing variants or gradually concretising it. Fricke found that a successful tactical approach has the characteristics of the balanced search. Note that, like Pugh and Cross, Fricke's observations on solution search started at the

19 **Fricke, G** 'Successful individual approaches in engineering design' *Research In Engineering Design* Vol 8 (1996) 151–165

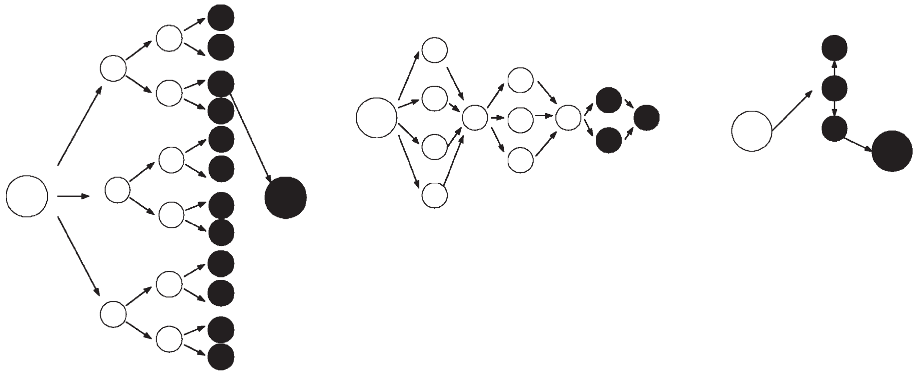


Figure 11 Three types of concept generation (from [19].

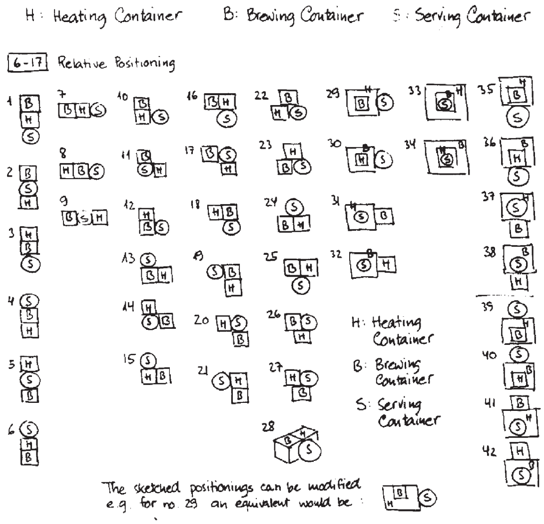
sketch level. He pointed out that promising concepts could be produced from different steps of synthesis, mixed with a series of narrowing down processes. Fricke's observation implies that a balanced search with multiple divergence and convergence could lead to successful designs.

Only a few approaches found in the literature have proposed methods to generate alternative spatial variants (i.e., spatial configurations) of solutions in the concept generation stage. However, different spatial configurations which are based on the same physical principle can represent different concepts, and some of them may lead to the development of innovative products. Therefore, in mechanical product design, it is also necessary to consider alternative spatial variants of a solution. Broadbent [20] emphasised the importance of this issue, and argued that there are many authors who consider only the checking and optimisation of solutions, rather than the creative step of developing alternative layouts of these solutions. Another example shown in Hubka et al. [7] for the design of a tea-brewing machine also contains the stage of generating alternative spatial configurations in the designing activity. The inputs required in the machine to be designed are cold water and tea leaves in appropriate amounts, and electrical energy, while the requirements of outputs are hot tea and separated leaves. Among others, three levels of solution abstraction, namely 'process structure', 'relative positioning' and 'outline concept' are used during concept generation. At the 'process structure' level alternative processes are generated to meet two main functions, (1) heating, and (2) extracting the

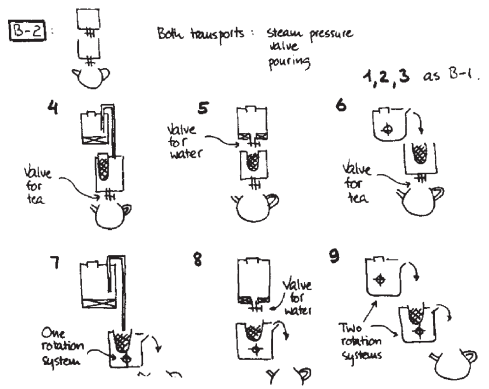
20 Broadbent J E A Spatial layout: an approach to the logical analysis of design Proceedings of the 12th International Conference on Engineering Design ICED'99 Munich, August, Vol 2 (1999) pp 787-792.

tea substances. The resultant processes lead to various function structures, each made of functional building blocks, to be replaced by ‘function carriers’ as abstract concepts. At the ‘relative positioning’ level (see Fig. 12(a)), the three main ‘function-carriers’: the heating containment (H), the brewing containment (B), and the serving containment (S) are identified. A large number of ‘spatial arrangements’ (see Fig. 12(b)), based on these three function carriers, are generated by the designer. Having decided on a suitable spatial arrangement, it can then be converted into various possible ‘outline concepts’. At the ‘outline concept’ level (see Fig. 12(c)), each element in the spatial arrangement can be realized by different possible

(a) ‘Main function carriers’



(b) ‘Relative Positioning’ of the three ‘function carriers’



(c) Possible ‘outline concepts’ generated from the selected ‘relative positioning’

Figure 12 Example of design outcomes by an engineering designer (from [7]).

variants. These variants are selected and combined into possible 'outline concepts'. These three abstraction levels are similar to the abstraction levels proposed in this paper. A 'function-carrier' is at a level similar to that of our basic elements, a 'relative positioning' is similar to a spatial configuration, while an 'outline concept' is similar in level to that of our generic physical embodiments. This gives some support to the appropriateness of the proposed abstraction levels. Besides, this example also implied that the solution space is explored by means of multiple divergence and convergence, which again gives some support to the proposed approach.

5 *Conclusions*

This paper discussed a possible 'ideal' approach for the development of concepts, in which a process of repeated divergence and convergence is used. The approach consists of a series of generation and evaluation rather than a single step of generation and evaluation. Levels of solution abstraction as well as activities at each level are described. Expansion of solutions consists of three synthesis processes. The processes of narrowing down solutions are screenings. It is argued that such an approach should increase the effectiveness of explorability of concepts with minimum compromise to the richness of the solution space explored.

The work is primarily introduced for use within the context of a computational framework. However, from the work of Hubka et al. [7] and Fricke [19], it appears that it should be useful also as a manual approach.

Acknowledgements

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Notes

1 Concept generation is described as 'concept formulation' by Pugh [2].

2 The level of detail of a sketch is considered similar to the range circumscribed by 'scheme' in French [6], 'sketches' in Hubka, et al. [7,8], 'ideas' in Pugh [2], and 'principle solutions' in Pahl & Beitz [9]. In mechanical design, concepts are often in terms of isometric or perspective sketches. These should be clearly understood by most designers.

3 Rectangular gears with rounded edges are kinematically possible, and provide output motion at a varying speed, with earlier uses in printing press mechanisms, see Brown [18].

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