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EXPLORING BASICNESS OF BUILDING BLOCKS FOR SUPPORTING INNOVATIVE CONCEPTUAL DESIGN USING THE BUILDING BLOCKS METAPHOR

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ABSTRACT

Supporting design of innovative conceptual solutions is an important goal of design research. Among various approaches to conceptual design, *Building Blocks* metaphor seems the most common. Synthesis models based on *Building Blocks* metaphor support development of design solutions by composition of a set of independent, modular structures from their knowledge base. The richer this knowledge base (of structures, as well as ways in which they can be combined, termed here as *Building Blocks*) is, the more the chances are for producing otherwise *innovative* designs using the knowledge base. The paper argues that an effective way of developing this knowledge is in terms of the *basic* set of building blocks. A definition of *basicness* is developed, and a scheme for identifying the *basic* set of building blocks, from among competing sets, is developed; finally, this scheme is explained using an illustrative example.

1 INTRODUCTION

Conceptual design is an essential phase of engineering design process [1], and the quality of the eventual design solution crucially depends on the quality of the concepts generated in this phase. There are usually more than one solution to a design problem to a design, and thus there is scope for producing better designs, if a large and wide-ranging solution space could be explored. Supporting the generation of innovative designs is, therefore, important, as has been reiterated in the existing literature [2, 3, 4, 5].

A common metaphor for conceptual design is the *Building Blocks* metaphor. In this metaphor, design solutions are composed of a set of individual identifiable parts. These parts are such that their behaviours can be understood in isolation, and when these parts are put together to form a solution, their individual behaviours can be composed to produce the overall behaviour of the solution. Examples abound in design synthesis literature [1, 6, 7, 8, 9, 10, 11, 12, 13]. The models underlying these require

* a given set of structures which have provided and required functions, and
* ways of combining those structures.

The models can then support the synthesis of solutions, to design problems expressed in terms of their functional requirements, as combinations of the given structures. The number of *novel* designs produced would depend on how *basic* the constituting structures (ie, given structures) and their ways of combination are. For example, if the given structures consist of gear-boxes (none of which is a differential), and not gears and shafts, then the design of a differential gear-box cannot be supported. On the other hand, if the structures include gears and shafts, then gear-boxes, differentials as well as many other designs can be supported.

Therefore, a parallel strand of research, examining the known solutions/structures, to discover the constituent *basic* elements and their rules of combination, should be established. Each time new original designs are found, these could be divided into either new *basic* solutions, or new rules of combination, or both, which would increase the repertoire of existing solutions and ways of combining them.

The synthesis models, together with a framework for supporting the extraction of this knowledge (of basic structures and combination rules), could then support innovative design in at least two ways:

* When no acceptable solution to a given problem can be found using the existing *basic* structures and rules of combination, then one knows that new knowledge is required.

* When a new solution to a given problem is found (which could not be produced using the existing ideas and combination rules), the new *basic* structures and rules of combination, of the new solution, extracted using the above framework, could now be used in the model to support a whole range of additional designs.

In this paper, we present some ideas towards achieving these, and show some examples of how these ideas might be applied in mechanical transmission design.

2 A DEFINITION OF THE *BASICNESS* OF A SET OF BUILDING BLOCKS AND AN APPROACH TO IDENTIFY THE *BASIC* SET

It has been argued in the Introduction that the use of *basic* structures and their rules of combination (hereafter called *basic building blocks*) in the synthesis of designs will increase the chances of producing a greater number of *innovative* designs. Before this could be done, a definition of what *basic building blocks* are, and a process for identifying them, are needed.

A set of building blocks is considered *basic*, for a set of structures, if the structures in the latter set can be created by combining the building blocks of the former, but not the other way around. Therefore, for a given set of structures, any other set of building blocks that can be combined to express its structures will also be considered a *basic* set. There can be more than one such set of building blocks. Among these sets, the one with the minimum number of elements will be considered the *basic* set. The underlying idea behind this proposition is that the building blocks constituting a more *basic* set can be more repeatedly used in the construction of compound structures. Also, the more *basic* a set of building blocks is, the more expressive it will be, and therefore, the larger will be the number of structures that can be constructed from these building blocks. These propositions can be used to produce a comparative definition of *basicness*:

(1) A set of building blocks can be considered *basic* for constructing a set of structures, if each structure in the latter set can be expressed as a combination of building blocks from the former set.

(2) Between two sets of building blocks, each of which can be considered *basic* for a given set of structures, the one which has the smaller number of building blocks is considered more *basic*.

(3) Between two sets of building blocks of the same size, if one can be used to construct all the structures that can be constructed from the other, and more, the former set is considered more *basic*.

The usefulness of finding the basic building blocks, in the context of design, is enabling the production of a large number of solutions, preferably from a small set of basic building blocks; the larger the ratio of the number of solutions that can be produced by using a set of *basic* building blocks to the number of *basic* building blocks, the more useful the basic set would be. The minimum value of the ratio is considered one, when a set of building blocks can be used to compose as many structures as the building blocks used.

When comparing two sets of building blocks, to find the one that is more *basic*, the general situation would be a combination of the cases (2) and (3) above, ie, the number of building blocks in the sets as well as the number of structures that can be composed by the building blocks from each set, will be different. In situations where cases (2) and (3) are conflicting, case (3) will be given preference, as producing a large number of solutions from a set of building blocks is the prime goal of this exercise. Suppose A and B denote two such proposed *basic* sets, and the number of building blocks in them, N_A and N_B respectively. Suppose the number of structures that can be composed from the elements in A and B respectively are N_{SA} and N_{SB}, where the two sets of structures are S_A and S_B (such that either $S_A \ldots S_B$, or $S_B \ldots S_A$, or $S_A = S_B$).

If the values of N_A, N_{SA}, N_{SB} and N_B are plotted on a two-dimensional space, where N_{SA} and N_{SB} are plotted along the ordinate while the N_A and N_B are plotted along the abscissa, two points, given by co-ordinates (N_A, N_{SA}) and (N_B, N_{SB}) will be obtained. A 45° line through the origin of the co-ordinates would denote the *usefulness line*, on which the number of *basic* building blocks will be the same as the number of structures composed from them. A point above the *usefulness line* is considered here *useful* (as the number of *basic* building blocks is less than the number of structures that can be composed from them), and a point on the line is *promising*, and a point below, *not promising* (the number of *basic* building blocks is more than the number of structures than can be composed from them). These categorisations give a heuristic guidance as to which set of building blocks is more promising to pursue. The orientation of a line drawn through the two points mentioned above can represent how the two points are spaced relative to each other and to the $N_{A/B}$-$N_{SA/SB}$ plane. There are five special cases* (see Fig. 1):

Case A. When the two points coincide. In this case, $N_A = N_B$, and, $N_{SA} = N_{SB}$.

Case B. When $\beta = 0$, where β is the angle from the positive abscissa to the line. In this case, $N_A > N_B$, and, $N_{SA} = N_{SB}$.

Case C. When $0 < \beta < \pi/2$. In this case, $N_A > N_B$, and, $N_{SA} > N_{SB}$.

Case D. When $\beta = \pi/2$. In this case, $N_A = N_B$, and, $N_{SA} > N_{SB}$.

Case E. When $\pi/2 < \beta < \pi$. In this case, $N_A > N_B$, and, $N_{SA} < N_{SB}$.

For each of these cases, more detailed relations can be found by investigating the special cases for each. These cases differ from each other with respect to the locations of the two points relative to the *usefulness line*. For instance, the special cases for Case B, when $N_A > N_B$, are:

Case B1. N_B, shown in Fig. 2a, on the *usefulness line*, and N_A below the *usefulness line*. This means:

$N_A > N_{SB} = N_{SA} = N_B$. This implies that using set B, which has a smaller number of building blocks than set A, a set of structures, equal in number to those produced by A and to itself, can be composed. This means that set B is more *basic* than set A, and is *promising*, while set A is *not promising*.

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* Apart from the five cases described, there can be more cases where $N_B < N_A$. However, these cases are equivalent to the cases where $N_B > N_A$, as A and B are interchangeable, and therefore, not discussed separately.

Case B2. In Fig. 2b, both N_B and N_A are above the *usefulness line*. This means:

$N_{SA} = N_{SB} > N_A > N_B$. This means that set B is more *basic* than set A, and both the sets are *useful.*

Case B3. N_B is above, and N_A on the *usefulness line*. This means:

$N_{SA} = N_{SB} = N_A > N_B$. This means that set B is more *basic* than set A, and is *useful*, while A is *promising* (Fig. 2c).

Case B4. N_B is above, and N_A below the *usefulness line*. This means:

$N_A > N_{SB} = N_A > N_B$, and that set B is more *basic* than set A, and is *useful*, while A is *not promising* (Fig. 2d).

Case B5. Both the points are below the *usefulness line*. This means:

$N_A > N_B > N_{SA} = N_B$. This means that set B is more *basic* than set A, but neither is *promising* (Fig. 2e).

In actuality, however, the structures that can be composed from the building blocks from a given set would be infinitely large, except in very restrictive cases. Moreover at the outset, the set of building blocks which could be used for composing structures might not be known. Therefore, we need to perform the process the other way around, ie, starting from a given set of structures, identify a set of building blocks that will qualify as *basic* according to the definition described before. This will require a systematic approach by which *basic* building blocks can be identified from a given set of structures, where each structure has specified functions.

Suppose the approach is to take each structure, such as structure E in Fig. 3, from the given set, and divide it into an arbitrary number of distinct building blocks (ie, structures and combination rules, such as structures E1, E2, E3, and rules R1, R2 and R3 from structure E), each of which also has *valid* specific functions, such that these elements can be combined to re-construct the original structures. By this very process, therefore, any set of building blocks so produced will be adequate to re-construct all the given structures (ie, for two different sets A and B of building blocks so produced, $N_{SA} = N_{SB}$). Therefore, cases C, D and E (where $N_{SA} \neq N_{SB}$) are ruled out. Moreover, as the number of structures is now just any given set, rather than all the structures which can be produced by a set of building blocks, the *usefulness* *line*, and the consequent categorisations (such as *useful*, *promising*, etc.) lose their strong significance. If this process is independently applied, twice, on a given set of structures, two sets building blocks A and B, say, would be produced. Suppose each such set is hypothesised as the *basic* building blocks set. Assuming that:

the number of elements in the set S is N_S,

the number of elements in the set A is N_A, and

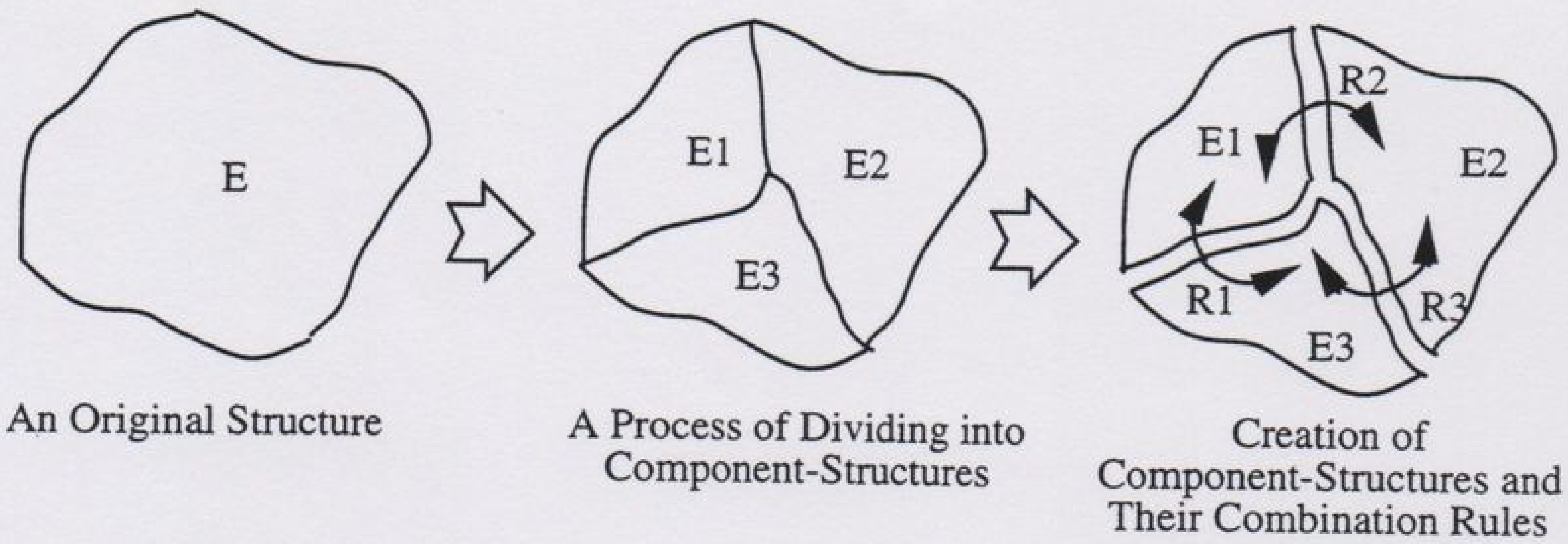
the number of elements in the set B is N_B,

we hypothesise that:

1. if $N_B > N_A$, then set A more *basic* than set B;
2. if $N_B = N_A$, then both the sets are equally *basic;*
3. if $N_B < N_A$, then set B more *basic* than set A.

The actual process, however, is a dynamic one, and more complicated. Suppose we start with a given set S of structures, and a number of hypothesised *basic* sets B_i (i = 1, 2,.., n) of building blocks, each of which can be used to produce the structures in S. Now, suppose S is increased to S', by introducing more structures . If these additional structures are also to be expressible in terms of the building blocks of the above *basic* sets, each of B_i must be increased (the increment in special cases could be zero) to B_i', by adding new building blocks. With each such increase in S, each basic set would produce a new data-point in an N_S-N_{Bi} plot. If a set of values of N_{Bi}, corresponding to a set of values of N_S, is plotted, these would produce a set of curves, such as the curves N_{B1} and N_{B2} in Fig. 4, each showing the change in size of the corresponding basic set with the change in size of the original set. The ideal situation would be to obtain a basic set such that it becomes asymptotic to infinity at a minimum value of N_S (eg, N_{B3} in Fig. 4).

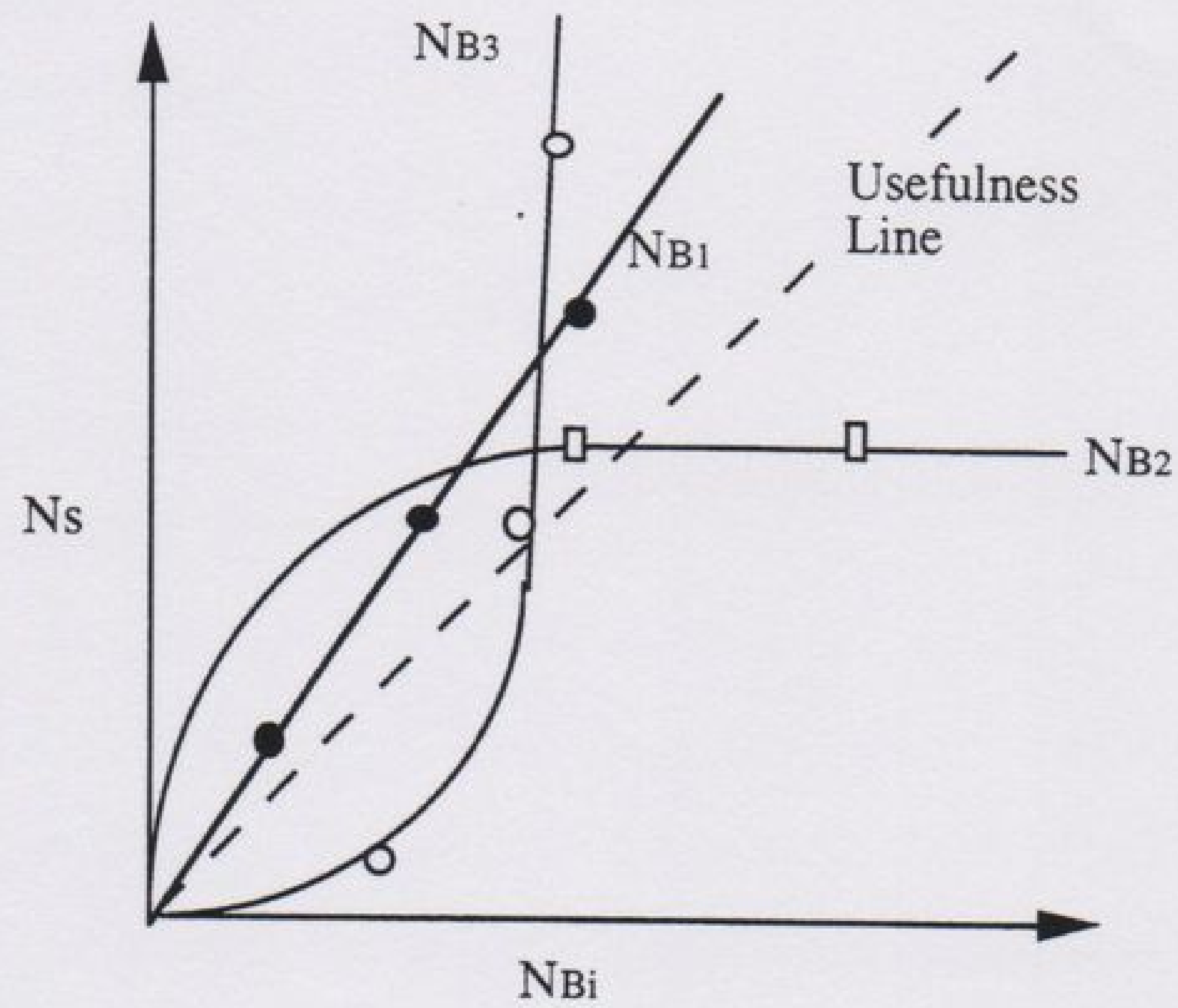
So, when there is more than one set of building blocks which can be considered *basic* for a given set of structures S, one of which happens to be the smallest, one cannot say with certainty that the same set will continue to remain the minimum set, with the necessary increments in its size because of a continued increase in the size of S, unless all the building blocks in the other sets can also be expressed using this minimum set. This means that the



E1, E2, E3: Component-Structures
R1, R2, R3: Rules of Combination

E: Original Structure

Fig. 3 A Process of Dividing a Structure into Component-Structures and Rules of Combination



Ns: Number of Structures in the Original Set

N_{Bi} (i =1, 2..): Number of Elements in the Basic Set B_i

○, ▯, ●: Data-Points (ie, Number of Elements) in Various Basic Sets for Given Values of Ns

Fig. 4 A Graph for Comparing Evolving *Basic* Sets of Component-Structures and Combination Rules process for finding the *basic* set should take into account the distinct building blocks created by all the competing sets, and try to minimise that set. So, the proposed approach is:

Step 1. Given a set of structures, find possible basic sets of building blocks for constructing the structures in the set, by dividing at least one structure into an arbitrary number of building blocks. If this is not possible, go to Step 4. Otherwise, follow Step 2 onwards.

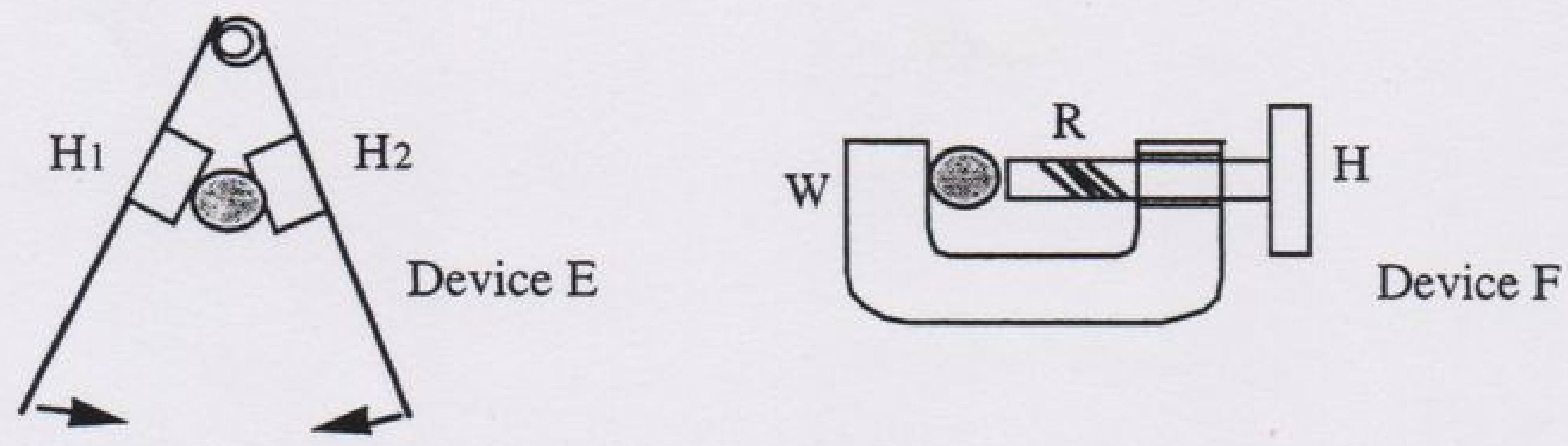
Step 2. Produce a new set which is a *set-union* of the structures from these competing *basic* sets, and the set of original structures. Take this as the new set of original structures.

Step 3. Produce a *set-union* of the building blocks in the *basic* sets. Eliminate all the building blocks, in this new set, which can be expressed as a combination of other building blocks in the set. The remaining set is now the new *basic* set.

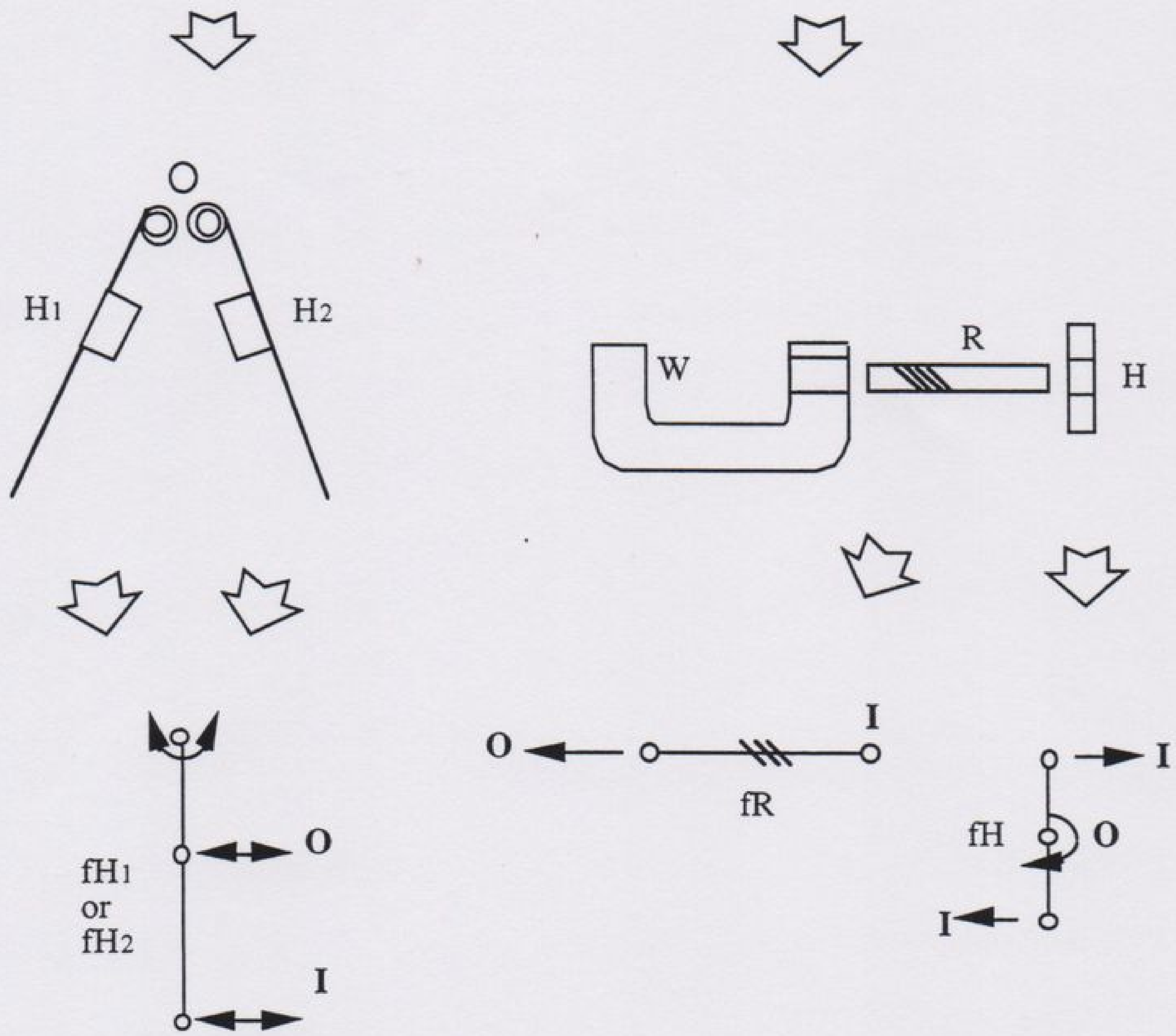
Step 4. Increase the size of the original set of structures by putting in more structures. Continue through Step 1 onwards, until the required increase in building blocks with an increase in S is sufficiently small, eg, curve N_{Bi}.

3 AN ILLUSTRATIVE EXAMPLE

As an example, let us consider two devices each of which can be used as nutcrackers (see Fig. 5a). In device E, two handles H_1 and H_2, which are pivoted at one end, are pressed towards each other, with the nut in between them, to get the desired effect. In the other device, a handle H is rotated to advance the attached screw R, which presses the nut, kept between the other end of the screw and the anvil W. We consider a set S containing E and F as the set S of structures for consideration. Suppose we consider only the handles H_1, H_2 and H, and, the screw R. Their functional equivalents are fH_1, fH_2, fH and fR (Fig. 5b) respectively. fH_1 and fH_2 are functionally equivalent, except that they work in opposite directions. Let us propose B_1 as a *basic* set of building blocks which contains fH_1, fH and fR (amongst others) as *basic* structures and the rule that "the input and output of two structures can be connected if they have the same rotation" as a *basic* rule. So,



a. Two Devices Which can
be Used as Nutcrackers



b. An Abstraction Process to Find the
Functional Equivalents of the Structures

Fig. 5 An Example of an Application of the *Basicness* Concept

$N_{B1} = 4 + x$, where x is the total number of building blocks to describe the remaining parts of the structures E and F.

Now suppose we propose a second *basic* set B_2 which, apart from having the x building blocks that were left while forming *basic* set B_1, has two other *basic* structures, ie, a simple lever fL (Fig. 6) and the screw fR (the same as that in set B_1), and the same rule as that in set B_1 as a basic rule of combination. In other words, the two handles fH_1 and fH in set B_1 are replaced by the lever fL to form a second set B_2. The sets are equivalent in terms of functionally explaining the example structures A and B, since the considered portions in E and F can be expressed in terms of the building blocks of these *basic* sets. The number N_{B2} of building blocks in set B_2 is given by

$$N_{B2} = 3 + x$$

Note that all the building blocks in set B_1 also can be expressed using the building blocks in B_2, see Fig. 6. If the structures in sets B_1 and B_2 are added to S to produce the new structure-set S', the number $N_{S'}$ of structures in S' is given by

$$N_{S'} = 6 + x$$

Here, $N_{S'} > N_{B1} > N_{B2}$, and N_{B2} is the present *basic* set. The points produced in this process are plotted in Fig. 7. The number of structures in S' can be increased now, and the same process can go on.

For any such attempt to be successful, what we need is a framework within which the functions provided by a structure, and the functions that are to be provided to the structure in order that it provides a specific function, can be deduced and checked, and assumed ways of combining structures can be validated and realised. The next three sections outline some preliminary ideas about such a framework.

4 SUMMARY AND CONCLUSIONS

In this paper, it is argued that one way of supporting conceptual design of innovative solutions is providing synthesis models, based on Building Blocks metaphor, with a

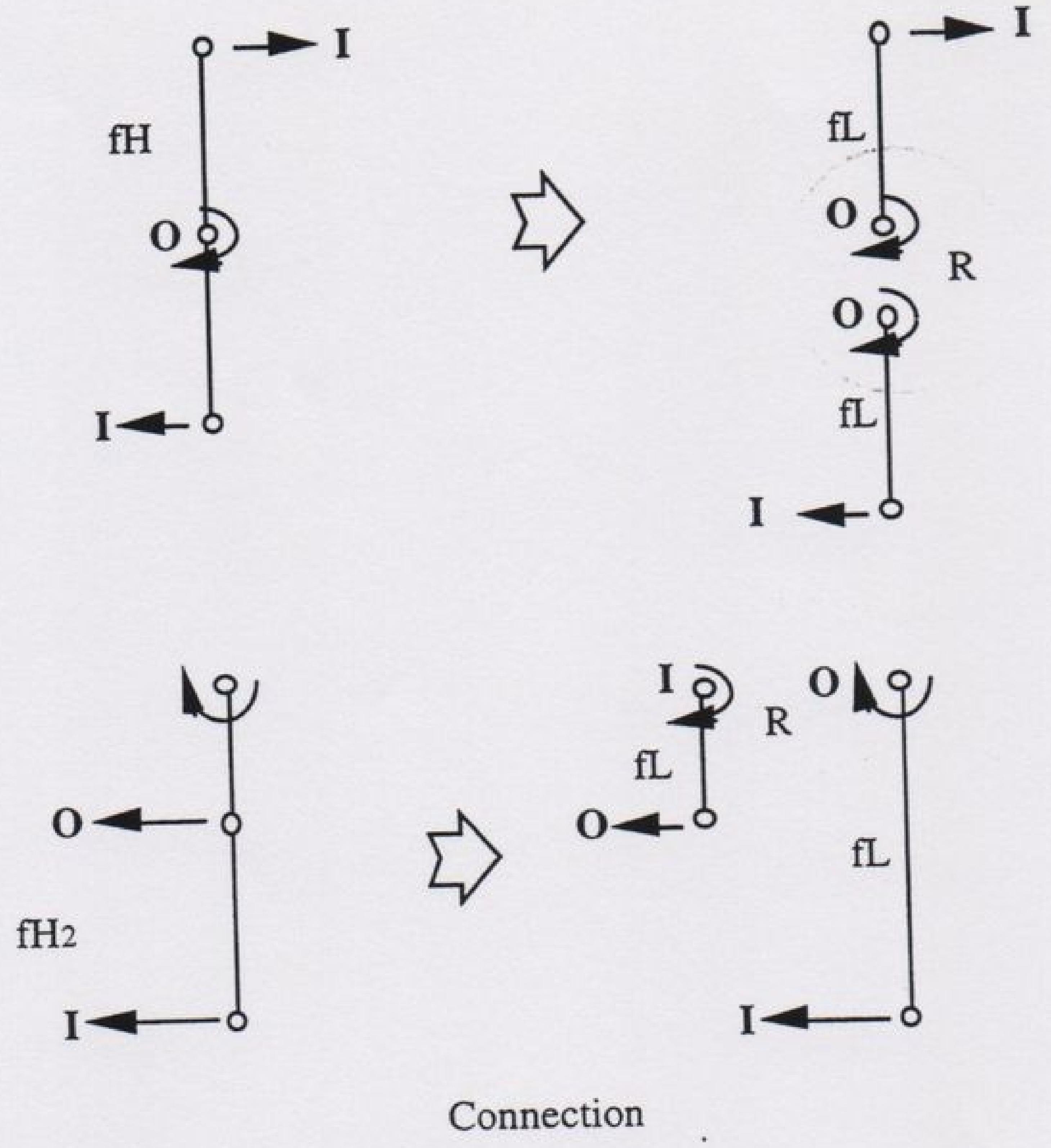
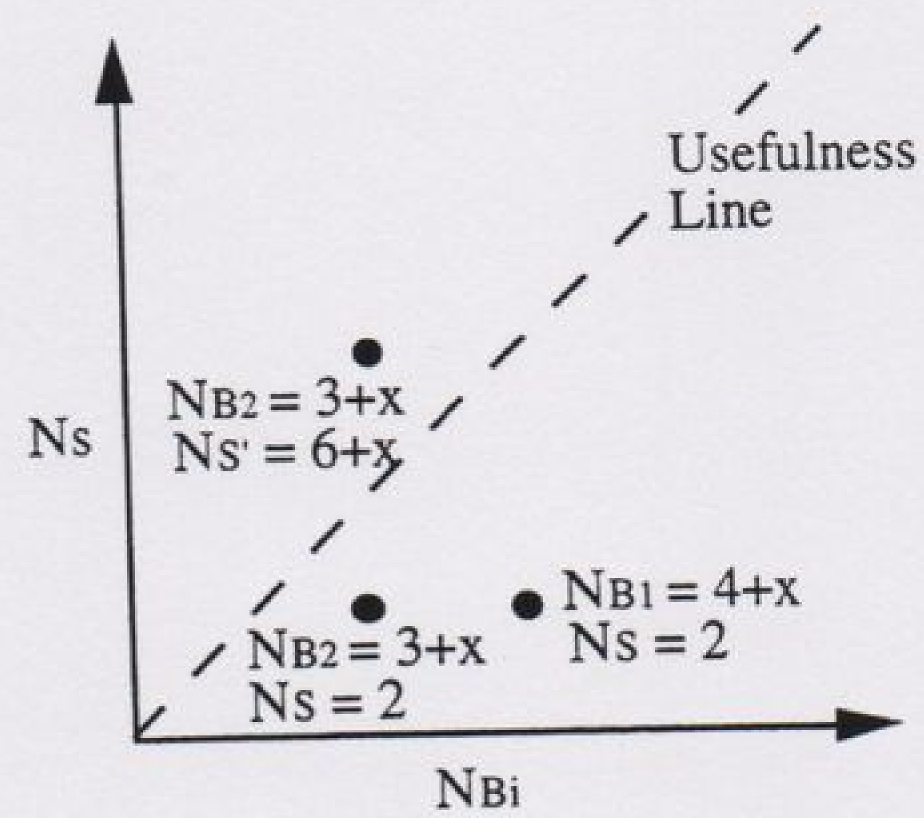


Fig. 6 Lever fL and Combination Rule R Together Could Represent Structures fH and fH_2



N_S, $N_{S'}$, etc. : Number of Structures in the Original Set
N_{Bi} (i =1, 2..): Number of Component-Structures and Combination Rules in the *Basic* Set B_i

Fig. 7 A Graph for Comparing *Basic* Sets of Component-Structures and Combination Rules knowledge base of the *basic* building blocks (structures and rules of combination) of the existing designs. The *basic* set of building blocks for a given set of structures is defined as the minimal validated set of structures and their rules of combination required to describe the given set of structures. The underlying reason behind the approach is that the more basic a set of building blocks are, the wider range is the solution space that it can describe, and hence the more the potential it has for producing innovative designs. With the evolving technology, each new solution to a design problem, which cannot be described by the set of basic building blocks in the existing knowledge base, would lead to new basic blocks being incorporated into the knowledge base, so that the model could then be used to support design of classes of otherwise innovative designs. An approach for identifying the most basic set from a number of potentially basic sets is proposed, and the approach is illustrated using an example.

Further work includes testing the feasibility of the approach for large scale applications, and its impact on the performance of the synthesis models.

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