An evolutionary process model of design

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This paper describes a model of design as a series of transformation processes and extends that model initially to include the behaviour of the designed product in its environment. This extended model is then recast through an analogy with natural evolution as an evolutionary process model of design through the inclusion of the evolutionary-style processes of cross-over and mutation and the introduction of design genes and the notion of inheritance from one generation to the next.

Keywords: evolution, design process

A designer is anyone engaging in an intentional, purposeful activity with the aim of devising a description (plan) for a product or artefact. In order to communicate the design to those responsible for its realization the description may take the form of formal documentation, it may be an informal instruction or it could simply be a concept which remains in the designer's head (in this view, the designer may proceed with the production himself and therefore no communication is needed). Before the final design is reached designers go through a series of processes involving partial propositions, their evaluation and modification.

Nevertheless, the nature of the activity called design is not fully understood. As a consequence we are usually more concerned with external manifestations of the design process in order to describe it. However, the early stages of the design process often do not have any external indications, since the first iterative steps of designing are only in the designer's mind. When the designer presents the first intermediate results, they may appear to be totally original and unprecedented. Yet, it is reasonable to assume that the early design phase, however inaccessible,

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would be much the same process as the later stages which we can already observe and understand to a degree.

Design solutions have often been seen as results of a sudden insight, mysterious inspiration or intuition (without a clear indication what these phenomena are). Little attention has been paid to the process of design and emphasis has been on the finished design description or, eventually, on the finished product or artefact. Novel designs are often very different from what we know and this may lead us to conclude that designs appear abruptly and are just the results of analyses of performance requirements and design constraints, with limited or no relationship to existing designs.

However, it may also be argued that the design process is nothing more than selection, refinement, modification and combination of existing designs or objects considering the current performance requirements and constraints. This is diametrically opposite to the former view. It assumes an intrinsic evolutionary process in design where any novelty, even a so-called innovative or creative design, is a result of recursive steps of generation and evaluation and where each new solution is based on pre-existing solutions.

1 Modelling the design process

Virtually all existing models including early models of the design process[1] imply a cyclic iterative procedure in design. All models deal with refinements of design, goal specifications, optimization of solutions, etc., but none of them is satisfactory in explaining the emergence of the first (most likely clumsy and unsuitable) concept or version of a design solution.

Moreover, current models of the design process are based on premises which do not fully take into account the environment in which designed products should perform. These models focus on individual aspects of the design in isolation. Omitting the role of the environment in a design model does not reflect the reality of the design process. It is suggested that designers have a mental model of the operating environment in mind from the earliest stages of designing. Often, in the later stages of design, physical or computer models are built and various environmental factors are introduced in order to test and optimize the design. Final tests are sometimes carried out on preproduction versions which are exposed to real operating conditions and changes are often made to the 'final' design as a result of its performance in these tests.

Since the existing models do not offer a completely satisfactory explana-

1 **Asimow, M** *Introduction to design*, Prentice Hall, Englewood Cliffs, NJ (1962)

tion of the design process, a search for a suitable metaphor for the design phenomena in other domains may be useful. The process of biological evolution as first formulated by Darwin[2] and more recently by neo-Darwinists[3] could give us a powerful analogy for the development of a model of the design process and methodology based on the mechanism of natural evolution and selection. The problem here is how to produce a plausible model which would explain the design process in its complexity including its early phase. This model should be understood rather as an explanation of an abstraction rather than the description of a reality.

Related research

Related research is experimental work by Rechenberg[4,5] and his colleagues from the Department for Bionics and Evolution Technique at the Technical University Berlin and work by Goldberg[6] on genetic algorithms at the University of Alabama. Rechenberg's focus is on applications of evolutionary techniques in mechanical engineering, and Goldberg's concerns are adaptive algorithms in machine learning, search and optimization. Goldberg's work was preceded by Holland's earlier interest in adaptive algorithms and systems[7] and von Neumann's work on cellular automata[8].

The references with regard to the evolutionary/genetic view of design are also sparse. The biological analogy in architecture and applied arts was used by Steadman[9]. Another writer who tried to use an analogy between the biological organisms and (mostly engineering) design was French[10] presenting a bio-morphic view. The subject of design genetics was tackled by Woodbury[11] from the perspective of shape grammars and rule mutations. The work of Jo and Gero[12] was concerned with mutation processes.

Definition of terms

Behaviour B effect of interaction of an artefact with its environment

Cross-over C process for combining variables from several structures

Design description D is a representation of designer's perception of structure by means of (natural or other) language

Environment E is world outside artefact

Function F purpose of product or artefact

Intent or *designer's intent I* is designer's purpose for design

Mutation M a process for changing variables of structure

Product or *artefact P* physical realization of design

Structure S configuration, arrangement, organization and form of product's constituents and their relationships. It represents the product or artefact from the point of view of the whole rather than of any single part.

2 **Darwin, C** *The origin of species*, John Murray, London (1892)

3 **Dawkins, R** *The blind watchmaker*, Longman, London (1986)

4 **Rechenberg, I** The evolution strategy: A mathematical model of Darwinian evolution, in Frehland, E (Ed.), *Synergetics – from microscopic to macroscopic order*, Springer-Verlag, Berlin (1983) pp 122–132.

5 **Rechenberg, I.** *Optimisation: methods and applications, possibilities and limitation*, Lecture Notes in Engineering, Springer-Verlag, Berlin (1989)

6 **Goldberg, D E** *Genetic algorithms in search, optimization, and machine learning*, Addison-Wesley, Reading, MA (1989)

7 **Holland, J H** *Adaptation in natural and artificial systems*, University of Michigan Press, Ann Arbor (1975)

8 **von Neumann, J** *Theory of self-reproducing automata*, University of Illinois Press, Urbana (1966)

9 **Steadman, P** *The evolution of designs*, Cambridge University Press, Cambridge (1979)

10 **French, M J** *Invention and evolution: design in nature and engineering*, Cambridge University Press, Cambridge (1988)

11 **Woodbury, R F** 'Design genes' in *Modeling creativity and knowledge-based creative design – preprints*, University of Sydney, Sydney (1989) pp 133–154

12 **Jo, J H and Gero, J S** 'Design mutation as a computational process', in Woodbury, G (Ed.), *The Technology of Design*, ANZAScA, University of Adelaide, Adelaide (1991) pp. 135–143

Processes as transformations

The design process can be regarded as a series of various transformations of function F, structure S, and behaviour B, into the design description D (See References 13 and 14). The following explanation of the design is based on a model of design as a process[13] and will be used as the basis for the development of the evolutionary design process model.

The most commonly used model would probably be that design is the transformation of function, i.e. the purpose of the designed product or artefact, into structure, i.e. the product's or artefact's constituents and their relationships

$$F \Rrightarrow S \qquad (1)$$

However, if we understand the design process as creation of a *design description*, or instructions to generate a product or artefact, this model is not complete because there is no clear path leading to the design description. It is also important to understand that between F and S there exists only an indirect transformation ($\Rrightarrow$).

Thus, another model would be the transformation of function to design description as in equation (2)

$$F \Rrightarrow D \qquad (2)$$

This model assumes that function requirements can be directly transformed to a description, which is not possible without any reference to the structure.

The following model implies that the design process is a transformation of structure into design description

$$S \rightarrow D \qquad (3)$$

This is the process of *documentation*[13]. This relation seems to be only partially complete because design is more than representation. The above examples of the simple design process models suffer from the same problem. All of them may be regarded as correct in one aspect, while they are incomplete in others. Also they do not take into account the way the product or artefact would be expected to act or to actually act, that is its *expected behaviour*, B_e and the *behaviour of the structure*, B_s.

13 **Gero, J S** Design prototypes: A knowledge representation schema for design, *AI Magazine*, Vol 11 (1990) 26–36.

14 **Umeda, Y. Takeda, H, Yoshikawa, H and Tomiyama, T** Function, behaviour and structure, in Gero, J S (Ed.), *Applications of artificial intelligence in engineering V: design* (1990) pp. 177–193

A model which deals with the structure and the behaviour of the structure, B_s, is given by equation (4)

$$S \longrightarrow B_s \tag{4}$$

which models the process of *analysis*[13].

The process described in the next transformation is that of *formulation* or *specification*, equation (5)

$$F \longrightarrow B_e \tag{5}$$

In this case function is transformed to a set of expected behaviours, that is the set of qualitative consequences of the function.

Evaluation in the design process comes from the comparison of B_e, with B_s,

$$B_e \longleftrightarrow B_s \tag{6}$$

The last two transformations needed to complete the model of the design process (as a combination of partial transformations) are *synthesis* (equation (7)) and *reformulation* (equation (8))

$$B_e \longrightarrow S(B_s) \tag{7}$$
$$S \longrightarrow B_e \tag{8}$$

Synthesis is the process of transforming expected behaviours to structures which exhibit those behaviours. Reformulation occurs when the structure that is synthesized brings with it its own behaviours or changes the behaviours expected of it.

Finally the general model is

$$\begin{array}{ccccc} F & \longrightarrow & S & \longrightarrow & D \\ \downarrow & & \downarrow & & \\ B_e & \longleftrightarrow & B_s & & \end{array} \tag{9}$$

where

B_e set of expected behaviours

B_s	set of behaviours of the structure
D	design description
F	set of functions
S	structure
$\leftrightarrow$	comparison process
$\rightarrow$	transformation process
$\dashrightarrow$	indirect transformation process

This model describes the design process as an activity with the purpose to convert the set of functions, F, through a series of transformations into the design description D. This process involves transformations which, when amalgamated to one general model of design process[13], would accommodate following design activities

- formulation (equation (5))
- synthesis (equation (7))
- analysis (equation (4))
- evaluation (equation (6))
- reformulation (equation (8))
- production of design description (equation (3))

From the model (equation (9)) the means of the transformations of synthesis (equation (7)) and reformulation (equation (8)) are not obvious. Synthesis is the process of structure determination based on the set of expected behaviours, B_e. The reformulation of the problem is a procedure necessary to modify B_e to resolve problems imposed by the structure.

Model of the design process including the environment

It appears that the model in equation (9) and some partial models/transformations used in its construction are incomplete. All activities in this model stem from the set of functions F, but it does not explain how we arrive at the functions. It would appear that F can be formulated only after we have an insight and understanding as to what we wish to achieve, that is, we can formulate the *designer's intent*, I. The transformation shown in equation (5), termed formulation (it may be understood as the design brief) derives expected behaviours from the set of functions. This should be extended by the inclusion of the designer's intent, I as in equation (10)

$$I \rightarrow F \qquad (10)$$

The next incompleteness appears in the transformation in equation (4).

the analysis. Here the set of behaviours of the structure, B_s, is derived from the structure, S, but it is not made explicit how this can be accomplished without any reference to the *actual environment* E_a, or the *simulated environment* E_s. E_s is derived from the knowledge about E_a. Also the set of expected behaviours B_e, should be derived from the set of functions F, which becomes the process of analysis in this model replacing equation (5) which was previously treated as the formulation. Thus the expected behaviour B_e, in turn can be transformed to the structure S. Hence new transformations are shown in equations (11)–(13)

$$F \longrightarrow B_e \qquad (11)$$
$$B_e \longrightarrow S \qquad (12)$$
$$E_a \longrightarrow E_s \qquad (13)$$

It is now possible to treat B_s as the result of the interaction process ($\Longleftrightarrow$) of S and E_s, that is as the simulated performance

$$S\,(\Longleftrightarrow E_s) \longrightarrow Bs \qquad (14)$$

The model in equation (9) also omits the area which is not always considered to belong to the design process, that is the transformation of the design description, D, into the product or artefact, P (equation (15)). We also have to consider the interactions between the product or artefact, P, and the actual environment E_a, equation (16) or between structure S, and the simulated environment E_s, which we could call real world interaction, equation (16), or the model world or simulation, equation (17), respectively

$$D \longrightarrow P \qquad (15)$$
$$P \Longleftrightarrow E_a \qquad (16)$$
$$S \Longleftrightarrow E_s \qquad (17)$$

The product's actual behaviour, B_a, in its actual environment is given in equation (18)

$$P\,(\Longleftrightarrow E_a) \longrightarrow B_a \qquad (18)$$

The simulated behaviour of the structure, B_s, or the actual behaviour of the product, B_a, is then compared with the expected behaviour as derived from the function, F. The comparisons, equations (19) and (20) are the evaluation of the quality of design and ultimately of the product or artefact

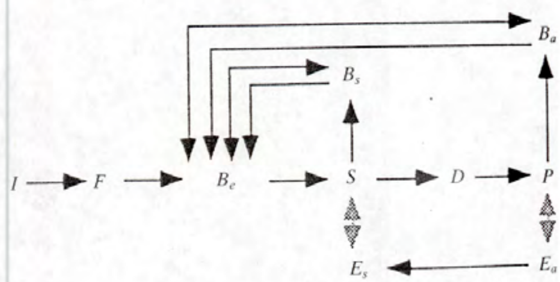
$$B_s \leftrightarrow B_e(F) \qquad (19)$$
$$B_a \leftrightarrow B_e(F) \qquad (20)$$

If the comparisons do not satisfy the requirements (i.e., B_s and B_a do not realize F), the set of expected behaviours has to be reformulated equations (21) and (22), hence

$$B_s \rightarrow B_e \qquad (21)$$
$$B_a \rightarrow B_e \qquad (22)$$

This revised B_e is some superset (or in some cases a subset) of the initial set of expected behaviours. This implies that the relationships in the design process interrelate the product or artefact with the actual environment in which the product or artefact operates.

The model of the design process given in equation (9) is revised to include the environment and is given by equation (23)



(23)

The model described in equation (23) contains the following activities

- formulation or design brief or specification (equation (10))
- analysis (equation (11))
- synthesis (equation (12))
- production of design description (equation (3))
- manufacture of the product or artefact (equation (15))
- simulation (equation (17))
- real world interaction (equation (16))
- evaluation (equations (19) and (20))
- reformulation (equations (21) and (22))
- simulated structure performance (equation (14))
- actual product or artefact performance (equation (18))

2 *The metaphor of natural evolution and selection as a basis for a model of the design process*

The evolution of biological organisms is based on two mechanisms. The first is the transmission of traits from an organism to its offspring through the passing of the genetic information from one generation to the next. The information may be altered in the process by means of cross-over and mutation. As a result of the modifications of the genetic code, populations of individual organisms with differing characteristics are created. The population serves as a pool of evolutionary 'proposals' for the second mechanism, natural selection.

The mechanism of natural selection works through the elimination of some individual members of the population because of their lesser ability to survive and hence propagate within the given environment. Remaining individuals which are better adapted to the environment therefore form a greater proportion within the population and the likelihood of propagation of their 'better adapted' traits through the transmission onto their offspring is increased with every new generation.

Natural evolution and design

The process of the evolution of biological organisms through the mechanisms of heredity and natural selection provides an analogy for the design process and the 'survival of the fittest' products. The similarity exists in three areas: firstly the cyclic nature of both processes; secondly the impact of environment on products or artefacts; and thirdly the continuity of designs. In design terms it means the existence of pre-existing design concepts at the beginning of any design process.

The cyclic process of generation of design proposals and their evaluation is quite clear. Designers generate design solutions, evaluate them, make alterations to recitfy problems, evaluate again and so forth.

The impact of the environment on the life of a design proposition (and later the product or artefact) has a pivotal importance as the selection and elimination mechanism in design. It appears that although designers do not always consciously use the environmental factors in the process of designing, they have a very good mental model of the operating environment and use it to develop a workable proposition. Later, after the design is represented outside the designer's mind, variables derived from the environment are used for evaluation and optimization, for example, building models and prototypes for testing. Without at least partial consideration of the environment, design is not rendered purposeful.

The existence of a representation of original products or artefacts or design concepts serving as the point of departure at the beginning of any design process is hard to prove because of a lack of knowledge about what is happening in the mind of the designer although there is beginning to be some psychological evidence for a number of hypotheses[15]. It is reasonable to believe that at the beginning of any design process there exists some pre-conception of a design solution to the given problem, in other words, there must always exist a proto-design to any design. This is not necessarily a formal design description, but may be a mental concept or design knowledge. The designer must acquire this cognizance to be able to design at all. This would be the instance even in the case of innovative/creative design and the initial design concepts may be called the inspiration.

The point of departure at the beginning of the design process may be a single existing design or it may be a meaningful combination of a greater number of existing designs or may be some abstraction or generalization of previous designs or design concepts. The existence of such a point of departure or an abstraction or generalization of such a point of departure is the basic premise of design as an evolutionary process.

Design is therefore an iterative cyclic process of generation and refinement of partial design solutions which are evaluated using a model of the actual environment. Based on the evalution, unsuccessful solutions are rejected and eliminated from any further process of design evolution, while more feasible ones are taken to the next phase. Further, to initiate the design process it is necessary to have a 'seed' design or design concept (regardless of whether it may appear clumsy, deficient, or even unrelated) at the beginning of any design process as the point of departure.

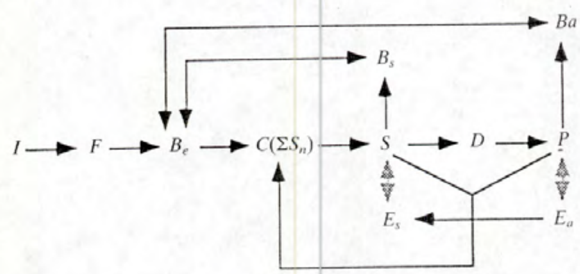
An evolutionary design process model

An evolutionary model of the design process can be based on the model in equation (23). The changes come from the introduction of time and the idea of a design population to the model. The activity of the designer is focused on two loops. The smaller one involves F, B_e, S and B_s; the larger one is formed by F, B_e, S, D, P and B_a. The small design loop is a subloop to the large one and the whole process is performed recursively until the final design is produced. Each time a new version of structure, S, is synthesized, its simulated behaviour, B_s, is evaluated against the set of required functions F. As soon as the expectations F are satisfied, the design description D, is produced and consequently the product or artefact P is manufactured. However, the product or artefact P may

15 **Purcell, A T and Gero, J S** The effects of examples on the results of a design activity, in Gero, J S (Ed.), *Artificial Intelligence in Design '91*, Butterworth-Heinemann, Oxford (1991) pp 525–542

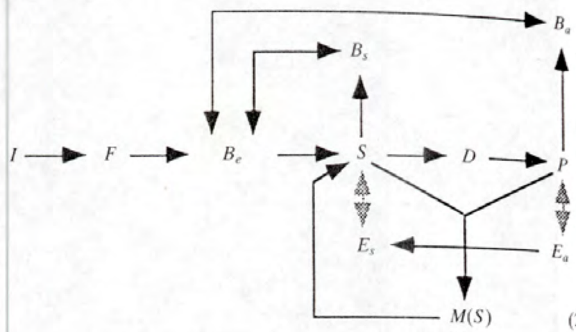
produce an unsatisfactory behaviour B_a. In such a case, the product or artefact must be redesigned and the process returns to the first loop.

The following model, equation (24), introduces the cross-over mechanism C as one of the mechanisms of evolutionary change. Cross-over allows for the 'cross-breeding' of different structures S_n from a population of structures to achieve a design satisfying the initial required function F. The combination of initial structures S_n represents the point of departure at the beginning of the design process. These structures are transformed to a structure S, which is then exposed to the simulated environment E_s, and consequently produces the simulated behaviour B_s. The structure S, is added to the population of structures ΣS_n, and this process is repeated iteratively until the comparison of B_s and B_e is satisfactory. The designer then proceeds with the production of the final design description and subsequently the product or artefact P, is manufactured. However, the overall process does not stop with the production of the product or artefact. The product, when placed in its actual environment E_a, exhibits its actual behaviours B_a. If the actual behaviours are not in accord with the set of expected behaviours, or if these actual behaviours are not satisfactory for any reason (the product of the design and manufacturing process P is not 'fit' for the given environment), the design process should resume in order to improve its 'fitness'. At the same time the models of the actual and simulated environments would be changed to include the new product.



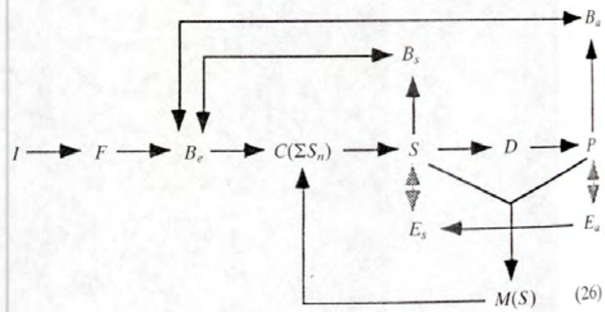
(24)

Similarly, it is possible to extend the model in equation (23) through the inclusion of the mutation mechanism M, as another mechanism of evolutionary change involved in the design process. The changes again occur in the structure S. The addition of the mutation mechanism to the model in equation (23) results in the model shown in equation (25). The operation of this model is similar to that in the previous model.



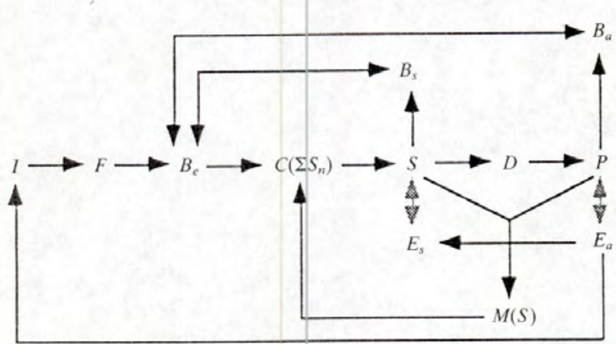
(25)

The evolutionary model of the design process (equation (26)) including both mutation and cross-over would be achieved by combining models (24) and (25). In this model the structure S, if rendered unsatisfactory for a further design process, may be mutated by the mutation mechanism $M(S)$, and then possibly the cross-over mechanism C, could be applied to the structure to change its set of behaviours B. It should be clear, however, that the mechanisms of mutation and cross-over are not mutually dependent and are not necessarily both applied during each step of the evolutionary design process.



(26)

Finally, to complete the model it is necessary to address the problem of the design intent I. The design intent I, is the driving purpose of the design, the identified need for design. The question arises why and where this intent comes from. It appears that the design intent may be created by the actual environment itself. The beginning of the design process is a side-effect of the evolution of the total environment within which the future product or artefact will exist. In other words, the design process is a part of the evolutionary transformation of the total actual environment towards a new state. The total actual environment E_a, becomes the driving force behind the creation of itself. This is expressed in the following model



(27)

Genetic operations in design

The genetic operations in design introduced in the above models (crossover, mutation and their combination), work on an appropriate representation of a design which enables the conservation of design traits and their inheritance between successive design generations. Replication (cloning) is not mentioned in the design context, since it does not have any more significance than straight copying of design descriptions.

Genes and genome in design

In biology the inheritance of traits is determined by genetic information contained in the molecules of DNA. The normal operations of an organism are determined by its genes. The genes are chained to DNA molecules, particular DNA molecules form chromosomes and specific configurations of chromosomes in turn constitute the genome or genotype of an organism. The organism which results from the expression of that genotype is called the phenotype.

Design heredity could be formulated analogically in terms of design genes and genome. However, to draw a direct analogy it may not be necessary to gain the insight provided by the natural evolutionary model. The design genome or genotype could be formulated to control the genesis of structure (growth of organism) and through the structure its resultant behaviour (metabolism and control). Hence, the genome in design would carry the complete information (or elements of knowledge) needed to produce an entire physical structure and its functioning, while individual genes (parts of the genome) would enable production of its individual parts or subassemblies and their mutual relationships. In other words, it is possible to look at the design genome as a set of instructions for the production of a structure.

Design cross-over

Design cross-over may represent a method leading to novel, innovative, or creative designs. Providing the design genetic information could have a uniform representation across all designs, or at least within the same 'design species family', then design cross-breeding and design genetic engineering should become possible by the exchange and transplantation of single units of design knowledge or entire parts of the design genome.

In terms of the design genome as outlined above, the cross-over could be regarded as a combination of individual design genes or their parts, that is a blend of sets of instruction for production related to two or more structures.

Design cross-over is a mechanism which could give designers a tool to combine different design concepts to achieve an entirely new behaviour (not only improvement or minor change) provided the behaviour can be recognized. This strategy is not new and has been used by designers to generate a novel design (such as combining parts of designs of an alarm clock and an explosive device to design a time bomb) when a comparatively small step in the design process may lead to a dramatic result in the final design.

Design mutation

The mechanism of mutation has been used in some instances[4–6,12]. Mutation constitutes an important and powerful design mechanism to change designs. However, the mechanism of mutation should also allow the production of new behaviours and hence functions, provided they can be recognized and perhaps to change fundamentally the make-up of the design.

Mutation can be seen as a variation of design knowledge in the context of the design genome, that is, mutation operates on the design genes. Design genes can be understood to be elements of design knowledge. Thus it would be possible not only to manipulate qualitative and quantitative knowledge in individual elementary units, but also the relationships of each subsystem within the hierarchical structure of the design.

In effect, design mutation takes place any time a product or artefact has been redesigned to develop a new type (as is usual in the automotive industry) or similar cases where parameters of design are changed, for example to improve parameters of the product or artefact, but the essential constitution of the product or artefact is to be preserved.

The environment in the design context

The environment in the evolutionary design process should not be understood as the situation surrounding the actual designing, but rather the circumstances under which the designed product or artefact is expected to perform. This corresponds to the actual environment E_a in the models in equations (23)–(27). This real world environment is used in the construction of the simulated environment E_s. The model of the environment may take various forms. In the early stages of the design process it could be just a mental model (interpretation) in the designer's mind. In later stages, using existing design methods and models, the environment is represented by partial and isolated elements against which design propositions are tested. In an evolutionary model of design the model of the environment should be as complete as possible to allow for unknown and unexpected interactions or combinations of interactions. The aim should be to expose as complete a model of the designed product or artefact as possible to as complete a model of the environment as is possible to allow for an evaluation of the 'fitness' of the design in that environment.

The actual environment not only poses physical constraints on the product or artefact, but also many others. Among these there may be constraints resulting from the co-existence of the product or artefact with other objects (with which it may compete for resources), the actual circumstances of the object's production (manufacture), probably the method and conditions of the object's design process itself, and most of all, since the major constituent of the actual environment are the final users of the designed product or artefact, the constraints imposed by them.

As is apparent from the model in equation (27), the actual environment should be understood as a systemic whole (including the product or artefact itself), rather than as an assortment of separate quasi-independent parts. This system of inter-related entities and processes evolves in time and the products or artefacts are created as indivisible constituents of this total environment through the design and production processes as the consequence of this progression. The relation between various elements of the actual environment in the context of the design process should be presumed to be a relationship of parts in a system of mutually inter-related and interdependent components in the ecological sense.

The model of the environment would be a representation of the environmental knowledge, that is the embodiment of the product or artefacts or products and their relationships within the useful vicinity of the product or artefact in question. In a way it could be seen as an extension of the expression of the structure, analogical to the hierarchic organization of the structure knowledge. The modelling of the environment in design is not a trivial matter and it is not possible to reduce or omit some of its components without paying the price in possibly ineffective designs. It is a combination of social, physical and other factors imposing constraints on the object, and/or interacting with the product or artefact in any way. The product or artefact's behaviours are generated through this interaction.

Impact of the environment in the design process

Regardless of whether or not the evolutionary pardigm is accepted in the design process context, the reality is that designed objects, when exposed to their actual environment, are regarded as successes or as failures according to their performance within this environment. That is, the process of selection and the survival of the best adapted products or artefacts is only possible within the actual environment. That does not necessarily mean that objects perform the expected function or that they display their expected behaviour, they may display a completely different behaviour than expected, and/or assume a rather disparate role than expected and yet be very successful. The actual environment is the final and ultimate selection agent for designed products and therefore the only measure of the quality of the design performing within a specific system.

However, it is not always possible to use the actual environment as a means of testing a design. In some cases it is not even possible to build prototypes for evaluation. Such designs are, for example, all one-off designs, such as large buildings or bridges. In such circumstances the simulated environment together with models of artefacts are all that is available.

Mechanism of selection in design

The process of natural selection is an indivisible part of evolution. In theory, biological organisms produce populations in which all members are exposed to the environment. Since (at least) some of the members differ in their genetic makeup and therefore in their constitution, they will interact with the environment in different ways. Some of them would not be better suited in this situation than their parent organisms and would not be able to cope and compete as well as others, becoming extinct as a result through the diminished ability to propagate. At the same time, other members of the same generation could be in better accord with the environment and therefore they would have an advantage over the rest of the population and subsequently would survive and propagate better. The genetic change would be reinforced and spread by means of cross-over and eventually such genetically altered organisms would dominate the population and become a typical example of its species. Of course, by then the species as a whole would have undergone an evolutionary change.

A parallel could be drawn between the process of natural selection in biology and the procedure of examining and rejecting design propositions and ultimately the acceptance or rejection of the finished product or artefact. The process of selection would be seen in the design context as the survival of the design/artefact which best fits the actual environment.

The mechanism of selection in design should probably be seen as the impact of 'market forces', that is the acceptance or rejection by end users, along with the impact of the physical environment. The users decide about the utility and desirability of designs and therefore about the survival or extinction of designs. Users are evaluating the set of actual behaviours B_a. The terms used in the evaluation of behaviours do not necessarily relate only to rational measurable characteristics. It is, of course, easier to design with a set of clearly stated and measurable objectives, none the less, designers understand that the results of their work are often judged on quite irrational grounds.

The selection and elimination of designs/artefacts are based on both measurable and immeasurable characteristics. The measurable ones would relate to economic and behavioural requirements, the immeasurable characteristics would be associated with other attributes such as the social values of design. From this perspective it appears that objects are in competition for common resources such as space, energy, and the favour of users, and they are part of what could be called the design ecosystem. They are an indivisible part of their environment along with all other objects, their users and all other items within this context.

3 Conclusions

This paper has presented an extension to the process model of design through the inclusion of ideas derived from a loose analogy with natural evolution and its genetic bases. These ideas appear to be an appropriate extension though the inclusion of genetics-based processes related to cross-over and mutation. The model is further extended through the inclusion of the actual environment.

Perhaps the most important notion in this paper is the concept of the environment and its role in the design process and the relationship of the environment and the product or artefact. The environment should be understood in the holistic manner as one whole including the product or artefact itself. The design process is then seen as an integral part of the evolution of the total environment and its progression towards a new state.