Annotated bibliography relating to the definition of the term 'Design Process' 1962–1995

Working paper preprint of Appendix 2 from
Love, T. (1998). *Social, Environmental and Ethical Factors in Engineering Design Theory: a Post-positivist Approach*. Perth, Western Australia: Praxis Education.

Introduction

There are two main themes within the literature on design process. In the first, design is a structured process in which information is processed and activities managed. The language of this outlook consists of morphologies, taxonomies, block diagrams, flow charts and system analyses. The second theme on design process is concerned with the human creative activity of designing and all necessary associated activities.

The literature on design contains a wide variety of proposals for the structure of the process together with morphologies and taxonomies of different aspects of designing and design theory. French (1985) commented on the extent of this variety whilst proposing his own block diagram representing the engineering design process:

> *Constructing block diagrams is a fashionable pastime, especially in fields like design where boundaries are imprecise and interactions legion, so that any ten experts will produce ten (or a hundred). They will all be different, and all valid. . . . They express only truisms, and yet they have a value for all that.*

Parnas and Clements (1986) argued that it is helpful for communication between designers and design researchers to use rational and logical descriptions of design processes even though designing is not essentially rational or logical. Sargent (1990) expressed similar sentiments:

> *In a sense it does not matter whether any such classification is true, but only whether it is an aid to talking*

The above comments point to a hidden epistemological difficulty in this area of design research. Both of the above positions indicate that a relativist position is appropriate to addressing the variety of different ways that design process can be conceived, yet they stop short of including those matters of theoretical perspective and metaphor that clarify relativist situations because of their inherent absolutism. That is, the impossibility of classifying definitions of design process in terms of objective 'truth' precludes being able to analyse the epistemological correctness of individual proposals if no attempt is made to analyse or take account of the assumptions on which particular models of design process are based (Indurkhya 1992; Stegmüller 1976).

Some researchers have addressed the epistemological issues on which their definitions depend. For example, Coyne and his associates have consciously focused on the epistemology that underpins design definitions and theory (see, for example, Coyne 1990c, 1991b; Coyne and Newton 1990, 1992; Coyne, Newton and Sudweeks 1993; Coyne and Snodgrass 1992b; Coyne, Snodgrass and Martin 1992). Other researchers have addressed the epistemological issues concerning relativism in design theory in other ways. For example, Jones (1970) explained his model of design process in terms of a means of classifying the information relating to a particular design; Siddall (1972) tied his model of design process to a definition of good decision-making based on value; and Ullman (1992) described his taxonomy of design process as an attempt to classify an evolving field. Each of these researchers has stated the perspective on which their model of design process is based, and made it possible, therefore, to analyse whether their model is consistent with its underlying assumptions.

The second theme in the literature on design process is concerned with design as human creativity. In many cases the literature in this area is epistemologically confused because defining design as a process assumes that design can be defined as a sequence. In essence, this means that to define design as a process depends on assuming that the design outcome is determinable. The concept of creativity, however, is dependent on the design outcome not being determinable, and hence there is an implicit epistemological contradiction. The origins of this difficulty lie in the early systematic models of design process, for example, the analysis-synthesis-evaluation model, which consisted of a sequential process that included a stage that was given the attributes of creativity or invention. These systematic sequential process models make sense from the perspective of managing designing or managing the flow of information, but as theoretical descriptions of designing as a human creative activity they are epistemologically incoherent because most of the elements included in the design process model refer to associated supporting activities rather than creative human designing.

These characteristics of the two different themes on 'design process' have already emerged in relation to definitions of 'design' in the first appendix where many texts that include 'design process' have already been discussed. This second appendix, therefore, focuses mainly on those details and texts that have not already been addressed.

1962 - 1969: design as a systematic process, epistemological difficulties, practice based process models

In 1962 at the Conference on Design Methods, Jones (1963) proposed a method of 'Systematic Design' that was aimed at reducing the amount of design error, re-design and delay, and, in addition, making possible more imaginative and advanced designs. His method was aimed at design problems where considerable departures from existing designs are called for, where large quantities of information are available, and where the design team has well defined responsibilities for development, free of routine design work.

Jones' built his Systematic Design Method around a framework of Analysis - Synthesis - Evaluation (ASE) and by this separated the intuitive aspects of design from the mathematically rigorous aspects of design with the intention of integrating the two into a more effective process. Jones' ASE framework has been widely accepted and used as the basis for models of design process. More recently, however, the ASE framework has been subject to practical and theoretical criticism in terms of its internal inconsistencies and its lack of coherence with real design situations (see, for example, Dasgupta 1991; Dietterich and Stauffer 1988; Stomph-Blessing 1989; Ullman 1992). The way that the ASE framework has been adopted by the field is rather different to the ways that Jones originally proposed, and few who based their theory on his ASE framework seem to have identified these differences.

Jones (1963) used the analysis-synthesis-evaluation framework for two purposes:

- To help designers distinguish whether their minds were acting logically, creatively or practically.
- To provide a system of notation to help designers record every item of design information *outside* their memories [emphasis in original]. In Jones' view of design, the mind moves from problem analysis to solution-seeking whenever it feels the need, and then the data can be recorded under the three categories of analysis, synthesis and evaluation.

The ASE framework has been mainly used in the design research literature, however, to describe or prescribe a sequential process of activities, and this is a different purpose to those epistemologically more justifiable purposes envisaged by Jones.

In the early 1960s, Alexander developed a different systematic design process based on probability and graph theory, and needing a computer for its application to anything more than trivial problems (Alexander 1963, 1964). In 1963, Alexander introduced this design process in relation to designing an Indian Village, and then expanded on his explanation of it in 1964 in *Notes on the Synthesis of Form.* Alexander's design process focused on the relationship between form and its context, and used a decompositional method that identified which aspects of a design problem are best considered as sub-problems on the basis of a weighted analysis of the relationships between all the design variables. His process was hailed as a major step forward in systematic design, but, although this design process appears to be almost completely automatic, it depended on a designer's ability to identify the relevant variables and the relationship between design elements. This meant that the human creative aspects of designing had become peripheral to Alexander's design process. Alternatively, if human creativity is viewed as essential to the concept of designing, then Alexander's process was peripheral, in the sense that it is a means of providing improved information to designers. Hence, it has much the same role with respect to a designer, and to design theory, as, for example, a mathematical means of calculating the stress in a bearing. Alexander recognised the underlying epistemological and ontological difficulties with his deconstructional design process, and in the mid 1970s, published an epistemologically and ontologically more sophisticated design process (Alexander 1977, 1979).

Roe, Soulis and Handa (1966) described the content but not the mechanism of a design process that included:

- Planning
- Systems
- Innovation and creativity
- The role of information
- Decision-making
- Value and utility

They regarded intuition or creativity to be a matter of four measurable psychological personality characteristics:

- That the designer is open to experience
- That the innovator must have a creative imagination
- That the innovator must exhibit detachment when necessary
- That the innovator must have confidence in his or her evaluations

Decision-making was seen as a matter of using probabilistic and weighting methods similar to multi-criteria or multiattribute optimisation methods. The aspect of design process to do with value and utility was viewed as problematic because of a lack of consensus in society about value and utility, and because of the difficulties of including issues of value and utility in a decision-making system. They suggested the use of a quantitative economic theory of value, and noted problems with regard to representing qualitative factors.

There are inconsistencies in Roe, Soulis and Handa’s proposals, particularly in how they reconciled issues concerning intuition and value with mechanistic methods. They avoided these problems to some extent by claiming that issues of intuition and value are not very relevant to technological design decisions.

Middendorf (1969) created a model of design process based on process management that was grounded in the day to day practices of engineering designers of that time. He noted that individual engineering designers each worked according to some iterative pattern, procedure or process, and suggested that this behaviour might be approximately described by the following steps carried out in an iterative fashion, but in more or less the following sequence:

1. Determine the specifications
2. Make a feasibility study
3. Search for patents
4. Develop possible alternative design concepts which are likely to meet the specifications.
5. Determine the criteria for making a selection and select the most promising of the alternative design concepts for further concentrated effort.
6. Develop a mathematical and/or a physical model of the selected design concept.
7. Use the model(s) to determine the relationship among the basic dimensions and materials of the product and the specifications.
8. Optimise the design with respect to as many of the selection criteria of step 5 as possible.
9. Evaluate the optimised design by extensive analysis on the mathematical model and tests on physical models.
10. Communicate the design decisions to engineering administration and manufacturing personnel by reports, drawings and verbal explanation.

Middendorf's model of design process had the advantage that if it were read aloud to experienced designers they would understand and probably concur. It represented, in a simplified manner, the idealised progression of activity that a designer might engage in but it lacked universality. That is, although many designers might agree that that is how designing might happen in a particular circumstance, it is by no means obvious that this description would apply to all designers in all circumstances in all engineering domains. Middendorf's design process is in effect a map that is useful for the management of designing.

In summary, in the period 1962 to 1969, the ways that design process was defined by the researchers reviewed here were based on the new systems perspectives that emerged in the 1960s. Researchers used these systematic concepts in a variety of ways to create models of design process that accorded with the design practices of the time but paid little attention to epistemological considerations and validity.

1970-1979: Design as methodological process, decision-making and optimisation

The 1970s started with Jones (1970) publishing his comprehensive collection of design methods which included discussion and analysis of many aspects of design theory. In *Design Methods,* Jones maintained a flexible position as to what might be the best model of design process, and expected it to depend upon circumstance and the individuals involved. Jones put forward the view that designing should not be confused with art, with science, or with mathematics. He claimed that it is a hybrid of all three, and pointed out that one of the differences between them is a matter of timing: that artists and scientists work in present time, that mathematicians work on abstract relationships that are independent of historical time, and that designers treat as real that which exists only in an imagined future. Developing the systematic perspective that he proposed in 1962, Jones expanded the 'analysis-synthesis-evaluation' model into: 'breaking the problem into pieces', 'putting the pieces together in a new way' and 'testing to discover the consequences of putting the new arrangement into practice', three aspects of designing that he called 'divergence', 'convergence' and 'transformation'. This new proposal may have been conceptually and epistemologically appropriate in, for example, Architecture where it is building form that is both taken apart and reassembled, but in most disciplines the pieces that are taken apart using analysis are not the pieces that are put together in synthesis. For example, in Engineering it is forces, masses, inertias and stresses that are the theoretical entities that are analysed, but it is gears, beams, shafts and cams that are the physically based concepts that are put together using synthesis.

Jones reconfirmed his position in 1963 that the main role of these terms is not as a representation of design process (as other theorists have taken it) but that the terms are more useful as a means of categorising information, design theories and methods for discussion and analysis. In addition, Jones was suggesting these categories as a conceptual framework on which to hang future theory. To quote,

> *The three stages . . . . do not necessarily fit together to form a universal strategy composed of ever more detailed cycles. They are more elementary than that, being merely categories into which the many loose ends of design theory, as it now exists, can be discussed at the inexact, or fanciful, level that our partial knowledge and partial ignorance permit.*
>
> *The three stages are here named divergence, transformation and convergence. These names are meant to refer more to the new problems of system designing than to the traditional procedures of architecture and of engineering design.*

This emphasis by Jones on the use of Analysis - Synthesis - Evaluation (or divergence, transformation and convergence) as categories for managing design theory-making is epistemologically and conceptually different from the way that they are used by many other researchers as prescriptive stages of design process.

In addition, Jones' proposals for viewing design as a systematic process tied his theoretical design process to business process in real organisations and included proposals for changes to organisational structures. He proposed that design processes should include marketing, design, production and sales and should contain several separate small-scale departments which act together within a product development department to realistically model a business's main operations. This concept of viewing design activity in its wider business context predates, by at least a decade, the view that design process is a central activity of commercial institutions (see, for example Andreasen 1985; Beitz 1989; Hollins and Pugh 1989; Pugh and Morley 1989).

The collection of papers relating to the *Symposium on Basic Questions of Design Theory* that Spillers edited in 1974 provides an insight into researchers' positions on design process in the years immediately after Jones' publication of *Design Methods*. For example, Purcell, Mallen and Goumain (1974) developed models of design process that were intended to utilise the increased availability of computers. Hence, like Alexander (1964), their models are neither based directly on some understanding of the theoretical and practical necessities, nor on whatever was best practice at the time, but on the possibilities defined by computer hardware and software development.

Motard (1974) suggested that creativity proceeds on two planes:

- The first plane relates to the inner state of the individual in which the creative outcomes are discovered via an internal symbolic language.
- The second plane is the external communication of those concepts formulated in the inner language, and this external communication helps the designer marshall an refine the internal concepts.

Thus, for Motard, the design communication media of charts, drawings, calculations and reports have a dual role as both a means of external communication with others and as part of an internal design process. If this is true, it has implications for the choice and design of the media used in developing, communicating and recording artefact or system details. Motard's proposals fit well with the observations of Booker (in Duggan (1970)) who concluded that:

> *Languages in general are not only useful for communication; they play an inherent part of our very thinking, for we tend to think in terms of the language we know. Drawing is of this nature, and he who can draw can think of, and deal with, many things and problems which another man cannot.*

These proposals about to the role of language and designerly methods of communication in design processes foreshadow research in the 1980s and early 1990s that came to similar conclusions (see, for example, Cross, Cross and Glynn 1986; Goldschmidt 1994; Tovey 1992a).

Harrison (1974) also used language as the basis for model of design process that automated design but, in his case, he based his design process model on linguistic theory. He demonstrated his outlook by applying it to the design of finite automata using the language of regular expressions, and concluded that this model of the design process could automatically produce the desired result for a client's specification. The main drawback of his design process, however, was that clients must always state their specifications in a complete manner and in the mathematically-based language of regular expressions. This means that the effort, and perhaps the process, of designing has been moved from the designer to the client. Harrison also suggested that predicate calculus, inductive inference and fuzzy logic were other possible approaches to a unified symbolically representable design process, but noted that these methods when applied even in the most constrained situations produced solutions which were unrealistic.

Wong (1974) based his view of design process on design practice in the domain of bioengineering and suggested that the typical design processes of bioengineering design is representative of design processes in most domains. He described his model of design process as follows:

> *It starts with a set of consistent principles capable of expansion and extension but bounded by the rules of logic, involves an operational discipline which leads to predicted action, and requires a feedback apparatus that makes meaningful evaluation and improvement possible.*

Wong used an hierarchical model that spanned between living systems and abstract concepts via what he referred to as the ‘mathematical formalisation of representation’. In essence, Wong’s description of his model supports the observation made earlier in Appendix 1, that definitions of design process depend on the concepts and theoretical perspective that are available in the domain in which they are conceived and expressed.

Altman (1974) suggested a model of design process aimed at organisational change as one of the consequences of design output. From this perspective, Altman argued that design process must include a consideration of human factors, and that this requires a qualitative means because the quantitative perspective that underpins most models of design process is limited in its ability to include human behaviour. He observed that most models of the design process implicitly assume quantitative logical procedures for modelling, evaluation and optimisation, and that including a qualitative perspective would necessitate fundamental changes to the way that the design process is seen and would have implications in terms of choice of the value system(s) to be used in the models, evaluative structures and optimisation methodologies. Altman's analyses, though sketchy and with little epistemological and ontological justification, pointed to the conclusions that have emerged as a result of the application of post-positivist perspectives in this thesis and predated them by a quarter century.

Westerberg, Stephanopoulos and Shah (1974) viewed the design process in chemical engineering as one partitioned into the sub-tasks of 'analysis', 'optimisation' and 'synthesis', and used these three terms in an industry-specific manner. Their design process starts with the synthesis of a design of an engineering system (the invention) which may be appropriate to the desired outcomes (presumably tested against some perceived needs). Then this engineering system is analysed to find out if it is suitable, and evaluated to determine its worth. They suggested an evolutionary means of automating the synthesis component by taking an initial process, modifying it then testing it for improvement. Their model of design process is strongly influenced by the modus operandi of chemical industries in that the focus—what is being designed— is an efficient means of synthesising the manufactured product, rather than the product itself. This leads to confusion between their use of the term 'synthesis' and its use elsewhere in the literature because in, for example, mechanical engineering design, the term 'synthesis' refers to the elements of the designed outcome.

Brotchie and Sharpe (1974) proposed a design process based on viewing urban planning design as design decision-making. They used a systems approach and included qualitative as well as quantitative data, but restricted the role of qualitative data to descriptive or labelling functions because all decision-making in their design process was done via a quantitative mathematical model. This meant that decisions involving qualitative data such as community attitudes or environmental issues could be included only by attributing quantitative weighting factors to them. The authors noted that there are problems with this approach because the factors which are weighted may not have a simple relationship with each other or with the system as a whole. Brotchie and Sharpe did not address the epistemological difficulties relating to value systems under which the weighting process is undertaken but their description implied a utilitarian model of value.

Gero (1974) focused on the limits of usefulness of systems analysis and mathematical modelling in a perspective on computer aided design process which included ethos and value judgements. He noted the symbiotic relationships between the developments in computer systems, systems methods and mathematical techniques. He suggested that, whilst researchers in these areas are happy to limit the scope of a problem by studying it in isolation, they rarely put the problem back into its fuller context to test the validity of their definitions of variables as either endogenous or exogenous or to test their assumptions about those variables. He suggested that the crux of one of the fundamental problems in computer aided design research is that the definition of problems is over-influenced by the means of resolving or analysing them. That is,

> *In order to manipulate the problem with a particular set of tools, the problem is so constrained that it allows no feedback to the ethos from which it was extracted.*

Gero argued that existing mathematical and computer-based tools of analysis force the definition of problems to be well-bounded regardless of whether or not this is their state in a larger system. He suggested that the failure, within the strict notions of scientific systems analysis, of attempts to include the contextual ethos of a problem or the range of potential value judgements pertinent to the view of the solution in its wider context is because the analytical tools that have been used are inappropriate or inadequately developed. Gero concluded that ethics formed the epistemological boundary for any model, and what was necessary was to extend the detail of models to that boundary. In summary, Gero was pointing to the role of ethics as an exogenous condition for models of design process, and arguing that those models must be able to unite systemic and ethical considerations. In terms of the philosophy of knowledge, Gero was suggesting that design theories must be coherent and well coordinated with their epistemological and ontological foundations.

Nevill and Crowe (1974) considered conceptual design as a process in which a designer is asked to generate a novel, highly optimal solution to a tentatively constrained problem. They viewed this design process as being represented by the stages of 'divergence' and 'transformation' of Jones' (1970) definition of design, and suggested that the conceptual design process is an optimum search through a maximally expanded problem space which consists of all the information which is known to or by the designer. They viewed their definition of conceptual design as better than other definitions that included concepts such as inspiration, insight and incubation, because the process was more compatible with computers.

Ostrofski's (1977) model of design process was based on a systems approach with a tree structure of discrete sub-processes, and assumed that designing and planning were equivalent. The measure of success for elements of his process was based on satisficing the needs of what he referred to as 'the production/consumption cycle'. Ostrofski's design process was also aimed at finding optimum designs that satisfied the above design constraints, and to this end he proposed using Criterion Function Synthesis as a method of quantitative weighted criteria evaluation for the comparison of candidate optimal systems. This method maps the design criteria onto probability space and enables the comparison of multiple criteria which are not necessarily independent. Ostrofski noted, however, that the proposed system depends upon human expertise and value judgements. That is,

> *Those who are evaluating the criterion performance and its relative value are experts to the extent that their decisions are rational, representing the maximum level of accuracy and knowledge at the respective stage of development.*

Ostrofski's model of design process was defined to enable the application of Criterion Function Synthesis as a method of quantitative weighted criteria evaluation for choosing optimal design outcomes. In essence, Ostrofski's design process is designed to create multiple designed outcomes that are quantitatively defined in the most appropriate manner to enable the efficient application of his preferred decision-making method.

In summary, the models of design process that emerged in the 1970s followed from the systematic definitions of the 1960s, but extended them in a variety of directions, in most cases with little regard for epistemological and ontological justification or coherency.

1980-1989: Mechanistic, mathematical, informatic and commercial models of design process, design as product development

In the early 1980s, some of the world's most prominent design methodologists expressed their dissatisfaction with the systematic design methods they had developed. This is seen in Jones' change of direction in *Essays in Design* (Jones, 1984a) and his discussion of design methodology in Jones (1984b). Similarly, Alexander (1980) argued for the importance of human values in designing, and, in 1984, spoke out against models of design process and methodology of the sort that he had devised in the mid 1960s. In spite of these criticisms the design research field continued in a positivist direction building rigid models of design process that were intended to result in the automation of design.

As in the 1960s and 1970s, many of these definitions of design process were couched in the concepts and terminology of the parent domain from which they emerged. For example, Furman (1981) an engineering design researcher, suggested a definition of design process similar to that of Haugen (1980) that was mechanistic and defined by forces, geometry and movement. Like Haugen, in parts he confused engineering theories that are used to provide useful information for designers with engineering design theory. Yet, Furman did not totally equate design theory with engineering theory because he argued that, in engineering, playing games with words, numbers, diagrams, graphs and computer programs had become an end in itself and that, 'the fact that they are models (approximations) only of the real physical world has often been lost sight of'.

Fukuda's (1983) description of the design process used in the design of large scale structures echoed Rittel's (1972a, 1972b) concepts of wicked design. He claimed that:

- *There are many 'difficult to quantify' factors involved in design and fabrication.*
- *Most structures, especially large ones, are produced to order. Therefore there is almost always the problem of lack of data.*
- *Various conditions in design and manufacturing change remarkably from structure to structure.*
- *Influencing factors are too many and too diverse, and furthermore the relations among these factors are too complicated.*
- *The quality does not depend upon a single manufacturing process alone, so that the interacting effect of processes must be taken into account*

Fukuda suggested that in a design process for large-scale structures it is important to fully utilise the limited amount of information and experience, and to extract the common and unvarying conditions of design and manufacturing. Fukuda's outlook on design process was pragmatic, and included humans as a way of addressing the particular difficulties in designing in this domain. Domain issues influenced Fukuda differently from Furman (1981) or Haugen (1980) in that his model of design process is directly tied to practice whereas the descriptions of design process from Furman and Haugen are built from the concepts and language that are a part of engineering analysis in their domains.

Biggioggero and Rovida (1985) presented a logical schematic model of design process based on the cataloguing of mechanical functions in order of increasing complexity. This is another example of a model that has its roots in the theoretical concepts of its associated domain. They noted that characterising the required mechanical functions had two distinct phases: qualitative choices and quantitative determinations. Their logical model of design process was well-suited to quantitative determinations or choices, but it is unclear how qualitative choices were incorporated into their design process.

Milacic and Polopovic (1985) defined a process for conceptual design in terms of the application of the theory of automata. They viewed conceptual design as a knowledge-based activity and, using a taxonomy of conceptual design information, they applied the theory of automata to these building blocks of knowledge. They concluded that the combination of theory of cybernetics, mathematical linguistics and theory of automata may be a basis for a general theory of conceptual design. They noted, however, that there are problems in defining a programming language for such a purpose and that optimisation methods must be performed through derivatives of regular expressions or other methods for converting non-deterministic automata into finite state deterministic automata. In essence, Milacic and Polopovic's model of design process is intended to facilitate the application of their mathematical methods, and, like the proposals of Harrison (1974), transferred much of the effort, intuition and creativity, and perhaps the designing, into defining the problem in the correct way.

Kuno, Kawagoe and Managaki (1985) also suggested the mathematical representation of design knowledge as the basis for a computerised design process. It appears however that, their proposals were tested only on design problems which were trivial or well defined. Their design process consisted of a two part sequence of 'primary' design and 'detailed' design. 'Primary' design is where designers collect together user's requirements and arrange and analyse them into specifications which the designers then use iteratively to determine reasonable objectives corresponding to the user's requirements, until a satisfactory design solution is reached. 'Detail' design referred to the design activities of determining geometry and other specific information in detail and was mainly concerned with properties such as size, heat flow and stress. Kuno et al noted that in real design situations 'primary design knowledge is undertaken within design paradigms whereby the design knowledge moves from concrete to abstract and vice versa in a dynamic fashion', whereas 'detailed design involves more practical directly related information'. They suggested that this is the reason why it was found difficult to model the primary design process. Kuno et al produced a view of design process that separates those essentially human aspects of designing from the mechanical determinable process relating to the manipulation of information. By assuming that knowledge and information are equivalent and that the essence of designing is the identification of correct information they failed to identify the epistemological and practical difficulties involved in attempting to devise a mechanistic process that includes human creativity.

The computer aided version of the engineering design process devised by Eversheim, Abolins and Buchholz (1989) had it as a linear flow chart relating to the stages of product development. In an epistemological sleight of hand they defined design process so as to exclude most of those elements which have proved intractable to other researchers. Their stages of product development are:

- Planning
- Conceptional (sic) Design
- Design
- Detailing

They excluded, however, 'Planning', 'Conceptional Design' and 'Detailing' from their model of design process. The design process was defined in terms of design activities that are separated into 'object neutral' activities and 'object specific' activities. 'Object neutral' design activities were data collection and calculations which might relate to any machine, for example, choices of bolt sizes or bearings. 'Object specific' design activities included the collection of data and calculations which are specific to the particular artefact being designed. In effect, they defined design process in terms of engineering calculations and the collection of engineering data, and, in this sense, their model of design process is engineering theory rather than design theory.

Dittmayer and Sata (1985) developed a mathematically based design process aimed at optimising product development. Their design process was divided between algorithmic and axiomatic approaches. Their algorithmic approach included the methods of mathematical analysis, and their axiomatic approach was based on axiomatic rules of thumb which have corollaries and which formed a decision-guiding structure. Dittmayer and Sata used a 'Universal Model of a Planning Process' to manage a design process defined in terms of their 'Product Development Model' (PDM). The PDM was divided into elements containing sub-elements of solution/evaluation/decision that could be arranged in series or parallel. Arranging the elements serially enabled modelling to be done firstly, at an abstract level and then at a more detailed level. Arranging the elements in parallel allowed the possibility of dividing the problem into units whose design might proceed in parallel. They concluded their analysis with four pieces of advice on using their systematic process of product development:

- Analyse existing products critically.
- Apply personnel resources to developing a large number of alternative solutions at an abstract level - without concrete detail.
- If final solutions have been developed using systematic procedures then the final choice is less critical.
- Do not use algorithmic methods when dealing with complex problems. Proceed iteratively.

In summary, Dittmayer and Sata's underlying perspective on design process was of making the best choice between a number of possible options that each satisfied the initial 'needs' or design constraints. Their algorithmic and axiomatic approaches were both to this end. The use of the term 'synthesis' implied the assembly of permutations of solution elements in the manner of the structure of their model of design process, and if this is the case then their model avoided all consideration of issues of human creativity and intuition.

For Arora (1985), iteration was the main characteristic of his mathematically based model of Optimum Design Process. His model, which was grounded in the domain of systems engineering, consisted of:

- System Specification.
- Preliminary Design.
- Detailed Design.
- Prototype System Fabrication.
- System Testing.

The model had feedback and feed forward paths, and was used to facilitate the application of algorithmic optimisation methods to the evolution of a design. There were other differences in the detail between Arora's Optimum Design Process and more conventional models of design process, particularly in the areas of needs analysis and evaluation of potential solutions. For example, the initial 'needs analysis' of traditional design processes was replaced in the Optimum Design Process by the 'identification of design variables, the cost function and constraints'. Similarly, the evaluation stage of the traditional design process, which involved assessing whether the solution performs satisfactorily, was replaced in the Optimum Design Process by comparing the design solution with its constraints and checking whether it satisfied convergence criteria. In addition, the traditional optimisation of design solutions via experience and heuristics was replaced in Arora's model by the mathematical optimisation of design variables in relation to the cost function. Arora claimed that the main gains of Optimum Design were that the designer needed to explicitly identify: the relevant set of design variables, a cost minimisation function and the constraints on the system. Arora's proposals are relevant to design situations that have a singular optimisation function, are well constrained and have quantitative variables whose relationships are well defined. It is not obvious, however, how well they are suited to design situations in which the variables, relationships and constraints are not related by simple mathematical functions, or not realistically expressible in numeric form, or where the optimisation process requires minimisation of many interrelated functions.

Dieter (1983) argued that, although optimisation procedures in a design process are intellectually pleasing and technically interesting, they often have limited application in a complex design situation. He stated that there is no universally acclaimed set of steps which leads to a workable design and claimed that design process is best represented by a chain of simple feedback loops of elements of 'information'/'design operation'/'evaluation'. Deiter suggested an arbitrarily chosen model of design process consisting of the following steps:

- Recognition of need.
- Definition of problem.
- Gathering of information.
- Conceptualisation.
- Evaluation.
- Communication.

He noted that sometimes the above steps might be carried out in parallel, and that feedback leading to iteration is expected. The underlying metaphor of Dieter's proposals was that design is problem-solving , and, from this perspective, Dieter identified that the final design depends on the viewpoint of whoever formally defines the problem situation. Dieter understood that qualitative issues involving human values have an important role in designing, and suggested that evaluation be performed by an impartial external reference panel. His overall preference for a quantitative perspective is evident from his proposals that human values and/or other qualitative issues should be expressed in terms of a quantitative measure of utility, ranging from 1 to 10, and that a multiattribute utility function should be used where necessary to combine individual utility functions. The core epistemological characteristics of Dieter's model of design process are those of pragmatism, problem-solving and positivism.

In 1982, Newell proposed an additional level in the hierarchy of system design which he called the 'knowledge level'. The significance of Newell's proposal for design research was that it appeared to address many of the conceptual difficulties relating to the representation of information and knowledge and their relationships with other aspects of design process. Newell explained the role of his 'knowledge level' in relation to the following hierarchy of electronic systems:

- Computer program (symbolic level).
- Register level.
- Logic circuit level.
- Circuit level.
- Electronic device level.

Newell's 'knowledge level' lies above the symbolic level and is characterised by knowledge as the medium on which rationality acts. From a positivist perspective, the 'knowledge level' integrated easily into models of human cognition provided that the human brain was viewed as a computer system and it was assumed that humans behave rationally. In effect, however, Newell's proposal simply moved the epistemological difficulties relating to the representation of the creative aspects of designing to a different theoretical nexus, because this computer based model of human cognition did not adequately include the phenomenological and contextual issues related to the way that creative thought depends on human values. These phenomenological and contextual issues challenge the basis of Newell's assumptions about the characteristics of knowledge and human rationality. Newell identified and attempted to address the challenge to rationality via Simon's (1982) concept of 'bounded rationality', but the difficulties relating to the dependence of knowledge and human cognition on human valuing remain. Newell's proposal of a 'knowledge level' was, and is, significant for those establishing positivist models of design process because it provided epistemological foundations for a quantitatively expressed relationship between design information and a rational basis for decision-making, and was well suited to situations in which designing is viewed as equivalent to searching through a solution space filled with quantitatively expressed objects. The weaknesses of Newell's proposal are those that can be attributed to its positivist outlook on cognition.

Clausing and Ragsdell (1985) argued that different models of design process are appropriate to different cultures and to different product development processes. In support of this position they cited the differences between models of design process in the USA and Japan. They claimed that it is difficult to separate design from other parts of product development, and produced a three-dimensional sequential and iterative model of the product development process that included the categories of : Needs, Concepts, Design, Parameter Design, Tolerance Design, Data Transfer, Produce, Test, Review, Improve. They defined design process as decision-making in a manner that they attributed to Harrisburger:

> *The design process is a trial and error sequence of choices among a number of alternatives, in which each decision is affected by compromise between a number of conditions and constraints. It demands meticulous attention to detail, co-ordination of a wealth of information, the search for ideas at each stage, and an overall necessity to achieve the best performance at the lowest cost in the shortest time.*

In short, Clausing and Ragsdell's model of design process was informatic and focused on decision-making, search and optimisation.

Hein (1985) viewed the design process as part of a concurrent model of product development in which the design of the product happened in parallel with the collection of market information, the establishment of a sales structure and the development of the production facility. He argued against a serial model of product development, and claimed that it is important to avoid a situation where the responsibility and information relating to a new product is developed and handed over from marketing to design to production and then sales. Hein's model of design process was participatory and commercial in the sense that all stakeholders or contributors to the design of the product contributed during the design process to maximise the potential profits.

Pugh (1985) argued that the conceptual development of designs occurs differently under static and dynamic conditions, and these differences are important in terms of business development and require two different models of systematic design process. He claimed that the ultimate success of a product arrived at by systematic means depends also on harnessing the creative ability of a multidisciplinary design team within a systematically structured design activity. It is not clear how exactly Pugh used the term 'multidisciplinary', and whether and how he differentiated it from 'interdisciplinary' and 'cross-disciplinary', or whether his use of 'multidisciplinary' would extend to an unrelated collection of experts from different disciplines. Pugh's model of design process was pragmatic, well-structured and addressed practical issues that are not included in other models of design process. Epistemologically, however, Pugh's models of design process were neither well-justified nor coherent, particularly because they depended on addressing a variety of different theoretical entities in an epistemologically similar manner.

Hubka (1985) took an economic rationalist outlook on design stating that,

> *The design process, like all other human activity, has to achieve the best possible results with the aim of increasing economic benefit for humanity.*

He suggested that the aim of engineering design research is to increase the efficiency of engineering design, and tied this argument to the emphasis on rationalisation proposed by Taylor and Gilbreth in the early twentieth century. Hubka noted, firstly, that rationalisation had not been the main aim of design research, and, secondly that although rationalisation had resulted in industrial productivity improvements of over 1000% from 1900 to 1960, productivity of design work increased only 20% in the same period. Hubka argued that further rationalisation should be possible in design practice. In essence, Hubka was proposing that the overriding priority for design research was to prescribe appropriate rational design processes and methods in order to increase the economic benefits. Hubka's analysis did not, however, extend to the necessary political and economic analyses that would, on one hand, indicate in which directions that economic benefit would be distributed and, on the other hand, provide the basis for the development of design processes.

Martyn's (1985) model of design process was also tied to commercial values, but his perspective on design process was societal—a perspective similar to that argued by Dilnot (1982):

> *The design process involves applications of technology for the transformation of resources, to create a product that will satisfy a need in society. The product must perform its function in the most efficient and economic manner within the various constraints that may be imposed. The major restraint is cost, although other factors such as safety, pollution and legal requirements will have to be considered....The sociological view of a product's place in society must also be considered. This will require an understanding of the structure and needs of society, and any changes that may occur, e.g. occupational changes or wealth, during the lifetime of a product.*

Martyn's design process was needs based and socially focused and, in terms of design theory, took an instrumental view of the role of engineering in the manner described in Chapter 1 of this thesis.

For Cross (1989), models of design process are descriptive or prescriptive. 'Descriptive' models of design process are those that describe what typically occurs in designing, whereas 'prescriptive' models are those that prescribe how designing should be undertaken. Cross claimed that prescriptive models are often better regarded as design methodologies because of their focus on algorithmic, systematic procedures. This algorithmic emphasis means that prescriptive models are also mainly concerned with well-defined and well-bounded quantitative problems which are more amenable to numerical definition and a classical mathematical treatment. In the main, Cross took a human-centred focus and regarded designing as a process of solving ill-defined problems. Although he did not state his stance clearly and definitively, it is apparent that Cross regarded a designer as a person who is able to synthesise solutions to problems which do not succumb to algorithmic analytical techniques and also able to perform multi-criteria evaluations of qualitative data. From this perspective, Cross also regarded design as a learning process in which a designer proposed solutions and in the evaluation of these solutions gained further knowledge about the design problem situation. Cross proposed a six stage model of design process that was symmetrical in terms of its attention to the design problem and its solution. The six stages were chosen to assist in the generation of solutions, to help redefine the problem and to decompose the problem and its solution into sub-problems and sub-solutions. These six stages were:

- Clarifying objectives
- Establishing Functions
- Setting Requirements
- Generating Alternatives
- Evaluating Alternatives
- Improving Details

Cross claimed that it was necessary to have a design strategy to manage the general plan of action for a particular design project and the sequence of particular activities and design methods used. He suggested that a design strategy should assist the designer by providing:

- A framework of intended actions within which to operate.
- A management control function enabling the designer to adapt their actions as they learn more about the problem.

He claimed that designers consciously and unconsciously used a variety of design strategies that included divergent, convergent, prefabricated and random search strategies.

To recap, Cross separated descriptive models of design process from prescriptive models and implied that prescriptive design processes are better regarded as design methodologies. This latter point accords with many of the analyses of this thesis in terms of improving both the terminology of design research and its disciplinary structure. Cross' perspective on design process was that designing is an essentially human activity that involves solving 'wicked' problems and that this also defines it as a learning activity. He did not claim that there is a universally applicable model of design process, and consequently he suggested that managing and planning the design process is an important aspect of designing. In this sense, Cross' position is pragmatic and embraces human, organisational and informatic perspectives.

In summary, the main focus of design research in the 1980s was the automation of designing via either rigid prescriptive processes, mathematical means, or the computerised manipulation of information. Alongside this focus on automatic design, and using the same algorithmic means and positivist perspective, was a strong drive towards developing automatic design optimisation processes. These prescriptive models of design process aligned well with the view that design was a part of a larger, commercially, organisationally and economically defined product development process. The systematic outlook on design process persisted in the background alongside the limited amount of research that maintained an assumption that design should be viewed as an essentially human activity.

1990-1995: Design process as design method, Total Design, design as reflection-in-action, histories of design intent, grammatically based design processes

The main themes in design research in the first half of the 1990s followed smoothly from the 1980s and moved the mainstream of design research further along the path towards the computer based automation of design. Most models of design process were based on a metaphor of design as transforming quantitatively expressed information, and most research avoided including any analyses relating to specifically human aspects of designing or epistemological correctness. Oxman (1995b), like Cross (1989) above, suggested that research into design process is essentially research into design methodology. From a methodological perspective, the lack of attention by the field to epistemological issues relating to theories of design process is surprising.

The metaphor of design as problem-solving still underpinned much of the research into design process especially in new areas such as software design. For example, Budgen (1995) described several design processes that utilised a problem-solving perspective alongside the conceptual tools of computer programming that focused on manipulating data. The systematic outlook on design process was also evident in many other publications but was used mainly to provide an outline on which to report other research (see, for example, Foqué and Lammineur 1995; Johannes 1992). Pugh (1991) combined the problem-solving and systematic perspectives in a comprehensive three-dimensional prescriptive model of design process that he called 'Total Design'. His 'Total Design' model covered all aspects of the development of products within an organisation. It included all inputs to the design process from market analysis through design and development to sales, and included output issues such as end of life analysis and recycling. He placed emphasis on the development of a complete product design specification (PDS) prior to any design work being started. The framework that he provided for developing PDS in theory allowed social, ethical and environmental factors to be incorporated via market forces. There appeared, however, to be an assumption that non-technical qualitative factors would be included in a quantitative manner using an economically rational theory of value and utility.

Ullman's (1992) taxonomy of mechanical design characterised the process and the research which accompanied it from much the same perspective as Pugh (1991), but he used a two dimensional hierarchical structure because the purpose of his taxonomy was descriptive. Unlike various other taxonomies of design process, Ullman not only classified information about the designed artefact but also classified information about the environment in which the design was undertaken and the characteristics of designers. The underlying perspective of Ullman's design process taxonomy was positivist and informatic, although his inclusion of considerations relating to design environment and designer characteristics point to the necessity of a post-positivist epistemology.

Dorst and Dijkhuis (1995) contrasted different outlooks on design and claimed that the two main explanations of design process were 'design as a rational problem-solving process' and 'design as a process of reflection in action'. They viewed the rational problem-solving approach as being based on Simon's (1969) theories and the reflective approach as being based on Schön's (1983) *Reflective Practitioner*. They concluded that viewing design as problem-solving was appropriate where design problems were clear cut and strategies were available for solving them, particularly with respect to information and the embodiment phases of designing. They regarded the reflection-in-action model as being better suited to the conceptual design stages, and suggested that Schön's (1983) model could be extended to including the rational problem-solving model. Lloyd and Scott's (1994) analysis of the models of design process used in architecture, engineering and computer science points to similar conclusions. They suggested that it is important to include the active agenda of the designer along with the designer's behaviour in developing a description of design process and that rational models of design process that were based on information about the design problem were insufficient to that task. In epistemological terms, the above perspectives do not appear to take account of the necessity for epistemological coherency in developing structural relationships between theoretical elements.

In 1992, Schön and Wiggins extended the reflective model of human activity and argued that viewing design as a reflective process strongly implicated the medium that designers used to record their designs. On the basis of observations of designers, they concluded that definitions of design process must take account of the fact that designers work in a medium, particularly that most designers work in a visual medium which conditions how they design. Their conclusions are supported by Goldschmidt (1994) and Tovey (1992a).

Ganeshan, Garrett and Finger (1994) also emphasised the role of the human designer but focused on providing a framework for design process for documenting the history of the designer's intentions through the course of designing a product. This outlook on design process is similar to that expressed by Jones (1970) and argued by Parnas and Clements (1986). This conceptualisation of design process as 'what designing happened in this situation' rather than 'how design should happen', or 'how designing happens in general' is essentially informatic. It contains information about the sequence in which design decisions were made, along with information about what decisions were made and why. In theory, the design process might include reference to qualitative phenomenological considerations, but, if Parnas and Clements advice was followed, the model of design process would be a rational and logical explanation that would filter out the arrationally of intuition and creativity. This makes sense from many viewpoints, but rationalisation of the design process record is likely to be unhelpful in the case where a design process history must be reviewed in detail, for example, in searching for new ideas or investigating a design failure.

The epistemological difficulties that relate to the research drive to automate designing were eased in the 1990s by greater agreement that the role of informatic design research developments was to assist human designers rather than to result in automatic design activity. This separated the epistemological issues relating to information about the design problem and solution from the epistemological issues relating to the human aspects of designing, and helped reduce the scope for epistemological, terminological and conceptual confusion. An example of research of this form was the development of a practical model of design process for the design of tubular steel trusses by Tizani and Davies (1994) Tizani and Davies developed a model of design process that was grounded in the current design practice in this domain. Their model of design process and its associated design methods was aimed at improving the quality of information that was available so that it enabled a human designer to make better informed decisions that would improve economic performance. A similar outlook underpinned Platt and Blockley's (1994) research into the development of an integrated computer based system that was aimed at improving the information available to both engineers and business managers in an organisation. The cultural theory that Platt and Blockley used as a basis for their design process was very different from the practical basis of Tizani and Davies' process, and led to an integration of models of product, process and organisation. This integration of the models of design process and design product was based on the earlier analyses of Dias and Blockley (1994) who divided process and product-based models of design into generic elements, and then identified extensive structural equivalence between both sorts of models. The reasons for the similarity between product and process design theories is also found in the meta-theoretical analysis that is defined in Chapter 3 of this thesis. The meta-theoretical perspective suggests that the similarity is due more to the epistemological structure implicit in any human theory-making than any actual similarity between products and processes.

The above models of design process that are aimed at supporting human designers also assist with the management of design and point to the change of emphasis in the early 1990s from 'trying to identify a universal design process' to 'providing the means to choose and manage an appropriate design process'. This can be seen in Whittaker et al's (1995) proposals for the development of an integrated design system (design process) for software design in which 'object-oriented' methods are used via different design process models to develop aids for designers. Similarly, Sivaloganathan et al (1995) identified four different groupings of design processes for use within product development situations, and suggested that models from these four groups could be incorporated and managed under the 'Design-Function-Deployment' design system.

The final theme analysed in this review of the literature of the period 1990 to 1995 is the linguistic approach to design process. This language-based outlook was found earlier in Harrison (1974) and is supported by the analyses of Cross, Cross and Glynn (1986), Goldschmidt (1994) and Tovey (1992a). The metaphor of design process that underpins the linguistic perspective on design research is that design elements can be regarded as nouns and adjectives and that operations on those elements are regarded as verbs. Examples of the computerisation of design in this manner are found in Coyne (1991a) and Coyne and Yokozawa (1992) in relation to architectural forms. Mullins and Rinderle (1991) extended this outlook into the mechanical arena, and proposed a grammatical approach to engineering design in which the design process consisted of the grammatical transformation of the characteristics of the design requirements, described in a formal language, into the characteristics of the designed solution. They argued that the application of formal grammars within a transformational paradigm opened the way for the computerised automation of design. Rinderle (1991) developed these concepts and demonstrated how a component based design artefact language can be parsed to check conformance to design specifications. One limitation of the grammatical outlook is that all aspects of a design and its context must be expressed in whatever formal language is used regardless of whether it is epistemologically appropriate. In addition, for the process to be epistemologically consistent with other design theory, it is necessary for the underlying assumptions to be consistent with theories relating to human design behaviour.

Summary

The main trends in the development of definitions of design processduring the period 1962 to 1995 follow the development of definitions of design over the same period described in Appendix 1. There is a significant epistemological divide between those definitions of design process that are based on managing and transforming information relating to a design problem and its solution, and those definitions that are based on behaviour of designers. The epistemological differences between these two types of design process models were echoed in Cross' (1989) differentiation between prescriptive and descriptive models. In most cases, prescriptive models of design process provided a defined sequence through which the design problem was transformed into its solution, and in this respect were mainly concerned with design situations that were well defined and could be rationally, quantitatively and deterministically expressed (Dorst and Dijkhuis 1995). This means that there is little epistemological difference between a prescriptive model of design process and a design method as some researchers have noted (Cross 1989; Oxman 1995b). This has led to the evolution of 'design systems' that include prescriptive models of design process and have essentially the same explanatory and conceptual role as the term 'design process' used to have (See, for example, Sivaloganathan et al 1995; Whittaker et al 1995). Descriptive models of design process that focused on designer behaviour were not as numerous as prescriptive models, but, in most cases, descriptive models used a similar positivist perspective to prescriptive models and this is clearly evident in the recent application of protocol analysis to building descriptive models of design process.(Dorst 1995; Oxman 1995b). An epistemologically helpful change that has occurred in the last decade has been the move towards viewing prescriptive and automated design processes as technical aids for designers. This brings the role of the human designer back to centre stage, but, more importantly, it reduces the epistemological and terminological problems that are associated with the conflation of analyses relating to human activity and the transformation of information.

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