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A Modelling Framework for 'Designing'

by

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A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of

Master of Engineering

Department of Mechanical and Aerospace Engineering
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and the
School of Industrial Design

Carleton University
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A Modelling Framework for 'Designing'

in partial fulfilment of the requirements
for the degree of Master of Engineering

Thesis Supervisor

Chair, Department of Mechanical and Aerospace Engineering

Carleton University
September 20, 1993
ABSTRACT

The immaturity of design theory is addressed; there is need for a simple descriptive understanding of designing, to serve as a foundation for education and practice, and to complement an intuitive and practical understanding of designing. Time, Information, and Domain are identified as fundamental characteristics. They are used as dimensions in a modelling framework, which demonstrates connections among existing design process models and information models. Within the framework, a Time-Results model can help improve existing design process models, and has the potential to model design process efficiency. Also within the framework, the Information Web can model the information results of a design project in a common format, and can be a computer-aided tool for design project information gathering, storage and display. Descriptive understanding is further augmented with a developed definition; "Designing is: describing a new possibility, which is expected to allow the achievement of a preferred situation."
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Glossary of Terms

design - a noun used to refer to the generic subject, or topic, of design. A definition of the subject is discussed at length in Appendix C.

a, (the), design - phrase(s) often used to generally refer to a collection of information that describes a specific object, artifact or product. It is difficult to assign more precise meaning. There are some by-products of the activity of designing which may or may not be considered part of the design of a product.

designing - is a gerund, which is a noun formed by adding 'ing' to a root verb. 'Designing' is the act of doing the action expressed in the root verb; 'design'. 'Designing' is the preferred word used in the thesis to refer to both the specific activity as well as the overall subject of the activity. An extensive discussion of existing definitions of 'designing' is contained in Appendix C.

the design process - a phrase used to refer to the various activities of designing that take place over time. 'The design process' is reserved to refer to the multiple sub-activities of designing, whereas ‘designing’ is
used to refer to the overall singular activity.

design science - is a phrase that is used most prominently by Hubka and Eder (1987), to refer to a body of knowledge which is required by engineering design, and to the scientific study of the design activity in its context. It would seem somewhat restrictive to confine its use to only engineering design, to the exclusion of other disciplines. In any case, the phrase is used sparingly in this thesis, generally in quoted reference to its use by others.

design theory - can be used to refer to a specific design theory, or as a broad reference to the subject of design theory. A theory can be strictly defined as having measurable variables that make up models, which can then be used to make hypotheses about the real world. In cases where a specific design theory does not strictly satisfy that definition, the phrase 'design theory' may be used less strictly, and more generally, to refer to any descriptive understanding of designing. This descriptive understanding of designing may contain concepts and models which attempt to partly or generally explain the real world practice of designing.

domain - in general usage, is a field or area. Domain is used more
specifically in the thesis to refer to the specific storage location of a piece of design information. This is of significance to the representational medium of the information, and to any subsequent handling and processing activities performed on the information.

**Internal, cognitive domain**

refers to the domain of the mind. This is the domain of ideas, and human mental processes.

**External, physical domain**

refers to the domain of physical objects, external to the human body. Information represented in this domain is usually directly accessible by a third party observer, in contrast to the inaccessibility of thoughts and ideas in the mind.
Chapter 1

INTRODUCTION

Existing scholarly views that describe our understanding of designing, from such disciplines as industrial design, architecture, and engineering, and especially significantly, views from within these disciplines, vary so greatly that views near the opposite limits of the range are mutually contradictory. Published views establish a range between the apparently conflicting extremes of stating that designing is well-defined and a design theory exists, to stating that it is ill-defined and no theory exists. At one limit are the claims for a design science, and design theory, as embodied in the work of Pahl & Beitz (1988), Hubka and Eder (1982), and the German VDI organisation (VDI, 1987). At the other limit, from design authors such as Ullman (1992), Hales and Wallace (1988), Coyne et.al. (1990) and Dixon (1991), are statements to the effect that a design theory does not yet exist, and that design research is in its infancy.

These two points on the range of views, which provide assessments of exactly how much is believed to be solidly and reliably known about designing, appear to be logically contradictory, as their assessments may imply that either we understand a great deal or we understand very little about designing. Not only is it likely that the truth lies somewhere between these views, but the differences in opinion obscure a greater issue. Beyond the differences, there is overall general agreement that the descriptive or
theoretical understanding of designing is still immature, and does not match the existing level of practical understanding.

Considering that there is both difference of opinion on design theory and agreement as to its immaturity, it is not surprising that there may be some differences of opinion as to the interrelationships of more specific design issues such as cost, function, time, process, activities, results, simplicity, complexity, reliability, liability, sequence, planning, analysis, synthesis, evaluation, simulation, optimisation, marketing, manufacturing, creativity, methodology, information, communication, teaching, learning, experience, CAD, CAM, expert systems, design representations, concurrent engineering, design for assembly, total quality management, and on and on and on. As any list of design issues gets larger, it would appear to become more difficult to judge the fundamental nature of the relationship of one issue to any other. These judgements would be necessary in order to develop an organised coherent structure of understanding designing. Along with the difficulty of making those judgements, it would appear that the need for just such an understanding is also likely to increase with the number and complexity of design issues.

It should be reasonable to expect that a detailed examination of the work and the concerns of a number of design authors, could reveal the foundations for their particular points of view and/or suggest some possible opportunities for agreement. These opportunities could lead to improvements in describing designing. This thesis is aimed at achieving just such an examination of views and a possible consolidation of them. It is expected that some
modifications of current views may be necessary, and these are suggested if and where necessary. Because this thesis results in adding yet another view to a collection of views that describe our fundamental understanding of designing, the potential exists that the problem of multiple conflicting views will be exacerbated. To avoid this problem, and to provide the intended benefit instead, every attempt was made to put this new view into a context of the existing ones, and to reconcile them.

This thesis is not limited to the examination of a design project or projects, in order to directly develop yet another view of designing or of the design process. Developing a theory from direct observation of design practice is a historical approach to developing a design model, and the past use of this approach has resulted in a great many theoretical models and observations about designing, many of which are presented in the literature review.

In order to build a modelling framework around existing design process models, this thesis does not focus simply on additional examples of design practice, but instead concentrates on observing many already existing observations of design practice. It serves as a meta-analysis of prior analyses, and takes an approach that examines those great many theoretical models and observations, in order to improve our direct understanding of them. As the intent of prior models of designing has been to improve our understanding of design practice, it is expected to follow in turn, that an improved understanding of prior models could result in an improved understanding of design
Some direct examinations of design practice are made in the thesis by highlighting two real design project examples in particular, involving the design of a food-product storage and mixing tank, and a hospital bedside computer terminal. These project descriptions are included in detail in Appendices A and B.

The detailed examination of our descriptive understanding of designing begins in Chapter 2, which provides a brief historical context of the past relationship of design practice and design theory. The effects of design specialisation are also discussed.

The literature review in Chapter 3 brings the historical context of designing up-to-date, and presents current models of the design process, current models or methods of information modelling, and a discussion of the domains of designing.

Chapter 4 presents the problems and differences that exist among current models and views of designing, including the view that design theory fails to match design practice. The problem addressed by this thesis is more carefully defined as the need for an improved descriptive understanding of the fundamentals of designing. This need for better descriptions of the fundamentals of designing has been specifically identified by Dixon (1991) and Ullman (1991), and improving the theoretical understanding of designing is a basic goal of both the European-based series of International Conferences
on Engineering Design (ICED) and the North American-based Design Theory and Methodology conferences sponsored by the Design Engineering Division of the American Society of Mechanical Engineers. The general aims of these conferences are to inform and improve upon the state of the art in engineering design. The specific aim of this thesis is to develop an improved description of the fundamentals of designing, and a corresponding modelling framework, to assist in bringing the theoretical understanding of designing up towards a level which can match and complement the existing intuitive understanding of its practice.

The main body of the thesis is Chapter 5, which begins with a simple description of an idealised design project. This description is at the core of this thesis, and it identifies some simple fundamental characteristics of designing, by avoiding the inclusion of a host of secondary issues. The approach taken is to attempt to describe designing as simply as possible. The characteristics found in the simple description are validated in examples of actual design practice, and are then expanded into a modelling framework. The modelling framework is described and checked against existing models of designing, and the design process. The fundamental characteristics of Time, Information and Domain are the three dimensions of a modelling framework of designing, and each dimension is discussed in turn, and in combination.

Chapter 6 is the conclusions of the thesis, including observations from the examination of current views, the insights gained during the development of the modelling framework,
and the modifications to current views of designing that those insights might require or imply.

Appendix A contains a case study of an actual engineering design project, which is titled "The Design of a Creme-Lite Mixer",

Appendix B contains a transcript of the description of an industrial design project, "A Bedside Computer Terminal".

These two case studies were chosen as typical examples of engineering design and industrial design projects, and because each is a fairly complete description of a design project from its start to finish.

Appendix C contains a discussion of existing definitions of designing. A concise definition of 'designing' is one important means of perception that can contribute to an improved overall understanding of designing, and the detailed development of such a definition is extensively discussed. The outcome is to suggest the definition:

"Designing: is describing a new possibility, which is expected to allow the achievement of a preferred situation."

A definition of designing is important to an overall understanding, but the development
of a definition is lengthy and although complementary, it is somewhat separate from the main body of this work, and was therefore placed in an appendix.

The main focus of the thesis is on exploring and improving various theoretical modelling descriptions of designing, and the main contribution is the identification of three fundamental characteristics of designing, and their use as dimensions in a framework for modelling designing. The exploration begins in Chapter 2, with a discussion of background influences on the current state of design theory.
Chapter 2

Background Influences on Designing:

History and Specialisation

Two background influences on design theory are the long history of design practice as compared to the short history of design theory, and the narrowed focus that may result from design specialisation.

The History of Practice and Theory

Although designing has been practised for thousands of years, and specific design facts and observations have likely been discussed and recorded for most of that time, it has only been in the last thirty years that academic attempts have been made to understand more than just specific applications, and attention has been placed on describing a non-specific, general design process of activities. General design processes have been described, or modelled, first by such notable writers as Asimow (1962), Hall (1962), Alexander (1964), and Archer (1965), and by many others since.

Because of the disparity in the subject of design between the long history of practice and the short history of study, before presenting a literature review that includes a collection of many of the existing documented models of the design process, mention is first made of the practical knowledge of designing. This practical knowledge of designing is
typically non-documented knowledge that would normally fall outside of the realm of a pure literature review.

Traditionally, designing has been learned by methods that do not involve documentation or general theory. Design and craft knowledge was usually learned by apprentices, and preserved as folk knowledge:

"residing in the folk collectively, but never wholly in any individual",

as described by George Sturt (1923), a writer and the owner/operator inheritor of his father's business. His book, "The Wheelwright's Shop", provides a rare and detailed documentation of the artisan's design and fabrication practices from a past way of life. The book also discusses how any evidence of what constituted a successful design would most likely have resided in the actual evolved form of a product or artifact, much more than it would in any individual's conscious mind or memory, let alone preserved in documented form.

Designing can also be understood and learned by personal experience, in a somewhat more abstract and formal way, not on the job, but in schools, by students practising the design and creation of artifacts, or their physical models, in a studio environment, subject to the watchful eye and the critical comments of the master. Many design professions continue to use this educational system of learning designing by practising designing. In it, students progress to become experienced designers, and absorb and develop large
amounts of personal knowledge about materials, artefacts, and construction techniques. This system, like the apprentice system, is also able to be self-sustaining over successive generations of designers, without requiring documentation of the imparted knowledge. Non-documentated knowledge is preserved as each new generation practises and absorbs the successful methods of the previous generation.

Because learning about the design activity through the documentation and study of general theory is relatively new, there has simply not been sufficient time to build, refine, and disseminate a strong theoretical body of knowledge. It is suggested that the study of the general design activity has also been somewhat hindered by the strong history of practical application. Design knowledge has for thousands of years been successfully passed along in non-documentated ways, and where knowledge has been documented, it is often directly concerned with very project-specific applications. With this successful alternative knowledge system in place, there is a lesser demand for academically documented general design theory. Lesser demand in the past, and a consequent lack of attention, may be one historical reason for the present immature state of design theory. Addressing this immature state, and making improvements to design theory could help resolve some disagreements about the theory/lack-of-theory state of designing, and could also result in a firmer theoretical foundation. A firmer theoretical foundation can complement practical knowledge, to enhance the future teaching and practice of designing.
Design Specialisation

It is suggested that any perceived weakness in design theory may also result from the breadth of the topic in comparison to the narrower scope of most design specialties. Documented knowledge of designing which is intended to be of a general nature, may be somewhat restricted because of the narrower focus of design specialisation. Each design specialty is legitimately only concerned with their own field. Because of this, they may inadvertently and unnecessarily self-restrict design definitions and models to their own fields of specialisation, even if the definitions and models could otherwise be quite general.

While definitions are specifically discussed in depth in Appendix C, the following examples demonstrate the concept of unnecessary self-restriction:

"A definition that contains the necessary ideas and speaks broadly of design follows.
'Engineering design is an ...'

(Middendorf 1986)

"Designing is defined as follows:
'Engineering design is a ...'

(Eder 1990)

The irony of attempting to speak broadly about design, yet constraining the definition to a particular design specialty, is obviously unintended by these authors. Unfortunately, it is not atypical of design activity authors from many specialties, and not just of engineering design activity authors. It is merely symptomatic of the division between
various academic specialties, and also of their respective schools of knowledge. The result is that the description and study of the general design activity is spread between specialties, and a general understanding is also clouded by self-restricted non-general design definitions and process models. There are only a few authors such as Alexander (1964), Gregory (1966) and Simon (1969) who have described designing in truly broad terms.

This thesis champions a broad point of view of designing. It is expected that any fundamental characteristics of designing should apply over a broad range, that need not be limited by the social constraints of educational and professional design specialisation. The influence of specialisation, and its possible narrower views, is resisted by examining the most general descriptions of designing, as well as examining the connections among various design specialties. Some particular connections that are examined are those that link general design theory to the rapidly developing world of computer aided software engineering, or information technology as it is also called, as well as to other academic fields such as cognitive psychology, semantics and linguistics.
Chapter 3

LITERATURE REVIEW

This chapter is organised in three sections. This organisational split was chosen as background preparation for the three dimensions of the modelling framework which will be developed later in the thesis. As such, the reasons for choosing this organisational split will be become more apparent to the reader as the thesis unfolds.

The first section is quite large, and presents most of the design process models that can be found in the literature. The presentation of a collection of this size is made partly for the sake of completeness of the collection, partly to show the wide variety within a narrow modelling type, and partly to show that there is no apparent convergence on any single model, or in any apparent direction of refinement.

The second section presents a number of approaches to modelling information. This section includes the entity-relationship approach to database design, which is a foundation for some computer aided software engineering (CASE) tools used in the field of information technology. Text modelling in semantics and linguistics is also included among the other examples of information modelling and diagramming in this section.

The third, and smallest section looks at existing design process models and discussions that refer to the various domains of design information. This section is the smallest as
domain, in the design information context used in this thesis, has not been extensively discussed in the design literature.

3.1 Models of the Design Process

Design process models can be in two forms, either graphical or textual. This section includes models in both forms, and presents the models chronologically. The models are presented without presupposing their true generality, and most do not clearly describe the breadth of their intended applicability. These models represent a prime source of descriptive data from which various observations can be made. The overall analysis presented in this thesis was not derived as much from direct observation of design practice, as it was from observation of the nature, structure, and details of these existing design process models.

For this section, in the context of this thesis, it is suggested to the reader that less attention need be paid to the details of each and every model, and more to the general nature and structure of the models, noting both their general structural similarities and the diversity of details within that similarity.

In his model of the systems engineering, development and manufacturing process, Figure 1, Hall (1962) was very careful to use Systems Engineering language, and reserved 'design' for a very small portion of the overall process. Hall referred to the
philosophical writings of Dewey (1938), and based his core model of problem defining, synthesis and analysis, decision making, and action planning, on Dewey's description of the Pattern of Inquiry, which involved problem analysis, idea generation, and idea evaluation. Hall's work is from the early days of systems engineering, and involved radio communications networks and the like.

Asimow (1962) was one of the earliest prominent engineering design authors. He diagrammed the chronological phases of a complete project (Figure 2), and further expanded the first three phases (Figure 3). He described these phases as the vertical Morphology of Design, and also described, but did not diagram, a horizontal problem-solving structure of design, consisting of a cycle of steps: analysis, synthesis, evaluation and decision, optimization, revision, and implementation. In developing this horizontal structure, Asimow made reference to Von Fange (1959), who described a Four-Step model of problem-solving, that included the steps define, search, evaluate, and select. Von Fange was associated with the engineering design research done at General Electric in the 50s.

Alexander (1964), had an architecture and math background. He describes a process of hierarchical decomposition to determine the components for an Indian village, in the example problem included as an appendix in his "Notes on the Synthesis of Form". He defines form as the solution to a design problem, and is that part of the world over which we have control. Context defines the problem, and is that part of the world which puts
demands on the form. The ensemble comprises both the form and the context, and fitness is a relation of mutual acceptability between form and context. Alexander concludes his discussion of these terms by saying that in a problem of design we want to satisfy the mutual demands which the form and context make on each other, to achieve a state of effortless contact or frictionless coexistence. He ultimately describes a Program as a tree of sets obtained by successive division and partition, and Realization as a tree of diagrams made by successive composition and fusion. While the Realization tree of diagrams represents the form, the Program tree of sets does not describe the context, but rather the set of possible misfits between form and context. He did not diagram the design process.

Archer (1965) wrote about designing as it is concerned with product design, which is the realm of the industrial designer. He provides two simple diagrams of the design process, the first being a breakdown of the basic design procedure (Figure 4), and the second showing the main phases of design (Figure 5). He concludes his work with a very detailed 229-step checklist for product designers, and a similarly complex arrow diagram.

Dixon (1966), an engineer, diagrams the design process in two levels (Figure 6). In the first, overall level, the activities are joined with double-headed arrows, allowing any sequence of work. The second level is a breakdown of the steps embedded within the engineering analysis activity from the first level. In the second level, the arrows are single headed, allowing a single sequence direction.
Vidosic (1969), an engineer, presents a 6-block flow chart model of the design process, with double-headed arrows throughout, allowing any possible sequence (Figure 7).

Jones (1970) wrote about designing from a broad and philosophical perspective, and was interested in the cognitive processes involved in bringing about change in man-made things. He acknowledges the widespread acceptance of the analysis-synthesis-evaluation model of the design process, but prefers to use a three stage structure of divergence-transformation-convergence. He does not diagram the design process, however, the 35 individual techniques and methods that he presents, are organised on an input-output chart that show six identified points in time, implying five stages. The six described points are: Brief issued; Design situation explored; Problem structure perceived or transformed; Boundaries located, sub-solutions described and conflicts identified; Sub-solutions combined into alternative designs, and; Alternative designs evaluated and final design selected.

Markus (1970) presents a diagram of the design process which has a repeating cycle of four steps, Analysis, Synthesis, Appraisal, and Decision (Figure 8). This cycle is considered to be the horizontal dimension, and is called the Design Process. The repetition of this cycle from Outline Proposals through Scheme Design and Detail Design to Production Information is considered to be the vertical dimension, which is called the Design Morphology. His background is in architecture.
French (1971), from a mechanical engineering background, presents an 8 step, largely linear boxes-and-arrows model, with some feedback to earlier steps (Figure 9).

Hillier et al. (1972), also writing about design from an architectural point of view, believed that when a problem is stated, the initial solution space is unlimited, although in the end only one solution is chosen. There is therefore a process of 'variety reduction' taking place. There are two initial sets of constraints that limit the solution space, the external constraints of the client, or the brief, and the internal constraints of the designer's range of 'instrumental sets'. "As the designer collects and organizes the problem data, and data about constraints, his conjectures acquire sharper definition. ...Conjecture and problem specification thus proceed side by side rather than in sequence."

When a conjecture holds up to the test of increasingly specific problem data, a halt is called to conjecturing and data collection, and a solution in principle is agreed to exist. About the model; "First, its core stratagem is conjecture-analysis rather than analysis-synthesis. Secondly the purpose of analysis is primarily to test conjectures than to optimize by logical or magical procedures." Cross (1981) describes this conjecture-analysis model as a solution-based model, while Hillier et al. themselves describe that conjecture and problem specification proceed side by side rather than in sequence.

Rittel and Webber (1973) described urban planning problems as wicked problems, but did not make any claim that all design problems are wicked problems, as was later suggested when referenced by Bazjanae (1974). They stated that wicked problems
should not be dealt with by a 'first generation' systematic methodology, but by a 'second generation' approach based on a "model of planning as an argumentative process in the course of which an image of the problem and the solution emerges gradually among the participants, as a product of incessant judgement, subjected to critical argument". Again note that this parallel process of problem and solution development was only claimed to apply to wicked problems, and therefore planning problems, but the claim was not necessarily extended to all design problems.

Bazjanac (1974), an architect, describes designing as a learning process. He states that the process begins with the formulation of the problem, and proceeds with the search for the definition of the solution, but he is quick to add that the formulation of the problem is not final. The designer continues to learn more about the problem and the solution, and occasionally documents what has been learned. He states; "Learning more is then perhaps the most important part of the process; redefinition and communication of the new formulation of the problem and the solution result only if more knowledge about them is acquired". Bazjanac did not diagram this parallel sequence process model.

March's (1976) model is based on three kinds of reasoning, Production, Deduction, and Induction (Figure 10). While no arrows are shown, the flow is described to be generally clockwise around the diagram. March's background is in architecture.

Darke (1979) expands Hillier's model of conjecture-analysis to become generator-
conjecture-analysis. She is, like Hillier, also an architect. A 'primary generator' is defined as being the initial concept or group of concepts that springs to mind early in the project, perhaps after some initial analysis, that provides the architect with a 'way in' to a problem. The primary generator is not the only possible or rational result of the initial analysis, but rather it becomes the tool with which to develop a conjectured solution, which when tested will produce further understanding of the problem.

Love (1980) wrote about the management of engineering design, and presents two diagrams, the formal iterations or phases of the design process (Figure 11), and the systematic steps within a design phase (Figure 12). In reference to the steps he comments that: "Each should be considered, although it is not always appropriate for each to be done in detail. It is not even necessary to do them in the order presented, but it is advisable that they all be considered prior to the termination of one of the phases of design".

Rsevski (1981) describes design as a trial-and-error process which includes:

1. Investigation and formulation of design problems,
2. Creation of tentative solutions,
3. Testing and checking of proposed solutions, and
4. Selecting the best solutions.

Although Rsevski teaches in electronic engineering and computer science, he discusses the design process as it would apply in designing any large system, whether that system
is a chemical plant, a town, a management organization or software for computers.

**Buat (1981),** an architect, describes a key property that all design process models possess: "the continuous need to revise the problem as the process of unravelling it unfolds. It is precisely this property that has often been regarded as characterising the process of design, where the instability of the problem causes it to constantly and elusively change during the course of its attempted solution." Although Buat does not provide his own model, his comments support those other models which have a parallel sequence of problem analysis and solution generation activities.

**Eekels (1982)** has a background in industrial design, and presents a model of how design fits into a structure of action (Figure 13), requiring both purpose design of a preferred state and means design of how to achieve that state. He also presents a divergence-convergence model of the industrial innovation process (Figure 14), which has the intermediate results of a 'strategy', 'product idea', and 'product design', before finally resulting in a 'new activity'.

**Hubka (1982)** presents a quite detailed general procedural model of the design process (Figure 15). His model is aimed at technical systems, and his work is focused on the design process as it is typically performed in European heavy engineering industries.

**Kardos (1983)** has a mechanical engineering background, and presents a cyclic model of
the design process (Figure 16). It has two cycles, one for simple optimization of a solution to a specification, and the other is the more complex design development cycle.

Pahl & Beitz (1984) may be considered, along with Hubka, Eder, and the VDI organisation, to form the German school of systematic engineering design. Their model is similarly quite detailed, and also tends to be aimed at the heavier engineering segment of industry (Figure 17).

The VDI-2221 (1987) model comes from the Verein Deutscher Ingenieure, a German industrial Society for Product Development, Design and Marketing (Figure 18).

Cross (1989) is an author and editor who is interested in design methodology as discussed in a range of fields. He presents two relatively simple models of the design process (Figures 19 & 20). He has written, along with Roozenburg (Roozenburg and Cross, 1991), about attempting to re-integrate engineering and architectural design process models.

Shigley (1989) is a writer of university-level machine design textbooks for mechanical engineering design students. His design process model allows return loops from every step, to every previous step, except the final one, which is presentation (Figure 21).

Coyne et. al. (1990) are interested in computer-based knowledge applications in
designing. They describe many different models of design in their opening chapter, including a hierarchical decomposition model (after Alexander (1964)), and the recursive model (Figure 22), before continuing on to describe knowledge-based design systems. They also state that there has been widespread agreement on the three phase design model (Figure 23).

Lawson (1990) does not present a design process model, but does present results of an experiment that showed architecture students tend to more often use a solution-based approach in solving design problems, as compared to engineering students who typically use a problem analysis approach. It is interesting to note that Lawson, Darke, and Hillier, all of whom Cross (1981) characterised as advocating solution-based approaches to design, all discuss designing in relation to architecture.

Suh (1990) is an engineer who presents a feedback control loop diagram of the design process (Figure 24). He describes design as involving four distinct aspects: "the problem definition from a 'fuzzy' array of facts and myths into a coherent statement of the question; the creative process of devising a proposed physical embodiment of solutions; the analytical process of determining whether the proposed solution is correct or rational; and the ultimate check of the fidelity of the design product to the original perceived needs." Suh describes the analytical process as one of verifying the correctness of the solution, and not the usual analysis of the problem. His main focus is on the presentation and explanation of the use of two axioms:
Axiom 1: Maintain the independence of functional requirements (FRs).

Axiom 2: Minimize the information content.

These two axioms are to be used as guides to making better decisions during the analytical process.

Pugh (1991) describes a total design activity model which includes all product design and development concerns from marketing through to selling (Figure 25). It is largely built around the early development of a detailed PDS, or Product Design Specification.

Eekels and Roozenburg (1991) discuss the similarities and differences between the scientific research and the engineering design process models, and in so doing present a model of the basic cycle in engineering design (Figure 26).

Ullman (1992) presents a model of the mechanical engineering product design process (Figure 27). It is interesting to note that in addition to the multi-step model, he also describes design as problem solving, involving the five steps of: Establish need, Understand the problem, Generate solutions, Evaluate and decide on the best, and Document the work; and design as learning, where more knowledge about both the problem and its potential solutions is gained throughout the design activity.
General Characteristics of Process Models

Over 30 descriptive models of designing are presented. About three out of four are represented graphically, and the remainder were described only in text. Despite the many obvious differences between the models, specifically in the number and the names of the component activities and their exact sequence, there are a number of similar characteristics of the models. These are:

The majority of the models use a similar structure to describe the process of designing, which is the activity-sequence approach of dividing the total design activity into an organised sequence of component sub-activities, which proceed, with iterations, between recognisable start and end points in time.

The described end result of a design project is some kind of description or drawing of a new product or artifact, and not the actual creation of the product.

Of the graphical models, the dominant similarity is in their use of boxes and arrows. The overall activity of designing is represented as being broken down into sub-activity boxes, with connecting arrows showing sequence. Most arrows show directionality, although in some cases the arrows are double ended, and merely show connection. In most models an overall sequence directionality is shown, but feedback arrows allow for the unlimited repetition of various activities,
allowing the flexibility of describing/prescribing a wide variety of sequences with varying patterns and numbers of cycles.

Three activities, or sub-activities of the design activity, predominate among the models, namely analysis, synthesis, and evaluation. These generally agreed upon activities may also be described as defining the problem, generating ideas, and evaluating the ideas to see if they resolve the problem. These activities are present in the most current models as well as in the earliest models by Hall (1962) and Asimow (1962). The description of these general problem-solving activities actually predates graphic modelling of the design process itself, having been presented by Dewey (1938) as component elements of his 'Pattern of Inquiry'.
Critical Observations of Design Process Models

There is a proverb which says that someone who has one clock is always sure of the exact time, and someone with many clocks is never sure. If the proverb is extended to design process models, it could suggest that someone who consults one design process model is always sure they know exactly what constitutes the design process, and someone who consults many models is never sure.

Among the graphical models, it is noted that while the boxes are invariably always labelled, the arrows rarely are. It is left to the reader's assumption as to the exact meaning of the arrows. The most cautious assumption is that an arrow conveys no more information than two particular boxes are related, and most probably in a time sequence. Explicit arrow labelling represents a large opportunity for conveying additional, more precise information about these and other graphical models developed in this thesis.

None of the existing process models suggest a method or means by which the efficiency of the design process may be measured, in terms of achieving some quantity of benefit versus some quantity of cost.

The models do not appear to be increasingly finer refinements based on earlier models. No evidence was discovered of the possible convergence of these process models in any
discernable direction, nor was there evidence that the whole design community has stated a preference for any one model. Most models are not presented as refinements of prior models.

The models are intended to have general application, as they are not aimed at specific projects. Most are not truly general however, as they are self-restricted to apply to a particular design specialty, for a project of average complexity and length of time. The overall range, and the range of best applicability, is rarely explicitly indicated. Despite the fact that many of these models are titled "The Design Process", it is logically apparent that not all of these different models can each accurately represent the same, singular design process, as used in any design specialty, for all design projects from the very simplest to the most complex, covering the shortest to the longest period of time. Each of the models could more accurately be labelled a model of "A" design process, not "THE" design process.

Some of these models begin to lose utility as leading guides to the design process because they present many choices of activities in many possible sequences. These choices of activities and sequence are presented with little or no guidance to assist in choosing among them. The more freedom of choice that a model gives a user, the less utility it has as an instructive guide to the proper activities in the proper sequence. Faced with a large variety of choices, and provided no guidance, the user must guide themself through the design process. If the user is guiding themself through the design process, then it
would seem that the model has lost some utility as a guide, and it has become only a suggested list of possible activities.

Because the models are intended to serve as general descriptions of the design process, they are not expected to always precisely match each specific project, and are allowed a certain latitude for variance and interpretation. It is because of this latitude that so many different models can exist, and still all be roughly correct, or at least acceptable. This same latitude, while allowing so many models to be used as roughly acceptable guidelines to the design process, can also prevent the refinement of these models into anything more precise, as the models are simply not expected to be precise tools.

The existence of process models of every possible sequence: forward-sequence problem-analysis models, reverse-sequence solution-based models, and no-sequence parallel-activity models, have the net effect of raising doubts as to which process sequence is best, or most accurately describes design practice. As these doubts have not been well-addressed in the literature, it would seem premature and/or incorrect for any one type to be labelled THE design process, indicating a single correct type, and denying the existence of the others. The alternative to denying the existence of the others, is to demonstrate the superiority of one type over the others, in some or all cases, for some or all problem-types. This has not been done. There appears to be no evidence in the literature of the existence of any testing or method of testing that has measured or could measure the performance of one type of sequence model versus another. The issue of a
'best' sequence is unresolved.

Despite the fact that the activity-sequence boxes-and-arrows type process model is the dominant type used in modelling designing, no evidence was found that its performance superiority has been conclusively demonstrated, in comparison to any other type of model. Given this lack of demonstrated superiority, one could wonder why the boxes-and-arrows model type is so prevalent. While it would be difficult to determine exactly why each author chose to adopt this particular form, two hypotheses can be suggested:

a) Easy and Obvious

The development and use of the dominant form of the activity-sequence design process model may simply have occurred as a result of natural human behaviour. Edward Hodnett (1955), from "The Art of Problem Solving", discussing problem analysis, wrote:

"The easiest scheme to follow is the chronological. In any process,...the obvious analysis follows the natural questions: 'What do I do first?', 'Now what do I do?', and so on."

He concludes the chapter with:

"Two simple decisions can improve your problem solving: (1) Take more time to analyze your problems. (2) Be sure the method of analysis you have selected is the most fruitful one."

If the choice of the boxes-and-arrows format has resulted from as simple a mechanism as natural human behaviour, i.e from first instincts as to what is easy and/or obvious, it may well be time to heed Hodnett's advice, and begin to
question this method of analysis. A more deliberate and extensive questioning of our analysis and modelling techniques could show that the standard method may not ultimately prove to be the most fruitful.

b) Functional Fixedness

Functional fixedness was a phrase coined by Karl Duncker, and which was discussed in design terms by Eugene Von Fange (1959). It refers to a mental block which hinders creativity, because of the tendency to see things as they have always previously been seen. This may apply in the case of the continuous thirty-year history of boxes-and-arrows design process models, as the very first models of the general design process by Hall, Figure 1, and Asimow, Figures 2 and 3, were of that type. Later authors may simply have been mentally blocked from considering alternatives because of functional fixedness, as they had always seen the design process modelled in the 'standard' way.

It is acknowledged that it would be difficult to prove the validity of these two hypotheses, as the models' authors are not likely to readily admit to careless or fixated thinking. Regardless of that difficulty, interesting questions are raised.

Why is it that many authors have chosen the boxes-and-arrows design process model form for modelling designing?

How does the boxes-and-arrows model work?
Is it always carefully chosen?

Have alternatives been explored?

Is it the best?

These questions may go largely unanswered, due to the mentioned difficulties in obtaining proper answers, and to the current lack of suitable techniques for measuring the effectiveness of the standard models and any alternatives.
3.2 Information Models

This second section of the literature review presents a number of approaches to modelling information. It discusses approaches other than the traditional forms of textual language and the pictorial engineering drawing. This section includes the entity-relationship approach to database design, and its resultant refinement into computer aided software engineering (CASE) tools and information technology. The section also includes a few other examples of information modelling and diagramming, including text modelling in semantics and linguistics.

Two traditional forms of recorded information are drawings and written text. Drawings are very good for recording the physical shape of objects, and the spatial relationships of various surfaces and features. Written text can also be used to describe physical spatial relationships, but it is especially useful for describing a much larger range of objects, concepts, and relationships, including more abstract ones such as ideas, time, emotion, values, meaning and aesthetics, or anything else that is not indescribable. Text is commonly found in the form of a linear string of words and sentences that in the English language is arranged from left to right in a line, line by line from top to bottom of a page, and page by page. Apart from this conventional publishing arrangement, our written language could be displayed, or imagined, as an essentially one-dimensional linear string of words and sentences arranged end to end in time, from start to finish.
This discussion of written language is undertaken as contrast to other methods of displaying language information. Some other methods, in the form of two-dimensional diagrams of interconnected words, are shown in Figures 28 to 31. Eder (1988) diagrammed the many connected topics which form the general context of engineering design and education (Figure 28). Hofstadter (1979) similarly diagrams all of the connected component topics of his Pulitzer Prize-winning book; "Godel, Escher, Bach: An Eternal Golden Braid" (Figure 29), and calls the diagram a semantic network. McLuhan and Davies (1986) describe a connected diagram of concepts as a 'cluster', and advocate the use of cluster-notes as an effective way to organize thinking and writing (Figure 30). The Ishikawa (1991) diagram is another that shows connected words and concepts (Figure 31). This type of diagram has a specific theme and a purpose that governs the connections that it shows, as it is intended to diagram all of the possible causes that may be producing a given defect in a manufacturing process.

It may be noted that in all of these diagrams, the concepts are recorded very simply, with a minimum number of words, and in most cases, the connecting lines or arrows are not labelled. This can leave some room for interpretation as to the exact relationships that were intended to be described among the various concepts. To produce a more explicit diagram would require fleshing out the concepts and labelling the connecting lines.

It may also be noted that the diagrams are not necessarily structured so that the spatial relationship of the concepts, or nodes, conveys any particular extra meaning.
A simple graphic unit in some of these diagrams is a circle connected by a line to another circle. In a more complex diagram, or graph, the circles can be described as nodes and the multiple connecting lines as links. The basic unit of two linked nodes is commonly known and used in different academic fields with different names for the components, the unit, and the overall diagram.

In semantics, Leech (1974) calls a unit of two connected circles and a joining arrow a "two-place (relational) predication", where the circles are arguments, and the arrow is a predicate. He uses this unit structure to build larger networks of branching "links" and "termini", when diagramming more complex sentences. Examples of Leech's diagrams of sentences are shown in Figure 32.

Perhaps the most extensive development of similar diagramming techniques is from computer database modelling, in the field of information technology. where apparently independent of any related work in language fields, Chen (1977) developed the concept of the entity-relationship approach to database design. This approach seems to have attracted a significant following in the database design field, judging from conference proceedings and a number of recently available texts devoted to the topic. Entity-relationship diagrams are also described as an important fundamental basis for object-oriented analysis, a currently popular method of analysis in computer software development projects (Coad and Yourdon, 1990).
An entity-relationship diagram is made up of entities as nodes and their relationships as the connecting links. Typical entity relationship diagrams are shown in Figures 33 and 34. Figure 33 shows a news archive information model (Veryard, 1992), and Figure 34 shows a diagram based on publishing academic papers (Teorey, 1990). There has been sufficient discussion in the field to result in a documented variety of diagramming methods, as shown in Figure 35 (Teorey, 1990).
3.3 Domain

This last section of the literature review examines domain, which in this context refers to the representational domains of design information.

The concept of a domain is simply a field, or area. In this thesis 'domain' will be used as a label for the location of a piece of information. By labelling the location, or domain, of a piece of information, it is possible to differentiate among various locations, each of which may have characteristics which determine how the information will be represented in that domain. For example, information in the cognitive domain of an individual's mind may be called an idea, and will have the characteristics of an idea, whereas information in the physical domain of a drawing may be called either lines, dimensions or notes, and will have the appropriate characteristics of those classifications. Even if the content of the information is the same, the form in which it is represented in different domains is dependent on the characteristics of each domain. Awareness of domain is useful not only for understanding how information is represented within various domains, but also for understanding what must occur in transferring or copying information from domain to domain.

Eekels (1982) uses the words 'realm' and 'region' in place of domain in his diagram, "The structure of action in general", Figure 13. It includes the "Realm of Material Reality" and the "Realm of The Mind". The latter is divided into two additional domains,
the "Region of Truth Statements" and the "Region of Value Statements".

In a paper that discusses sketching as visual thinking, Radcliffe and Lee (1990) discuss "the cognitive domain" and "the physical domain", as the two domains between which an idea is transferred. These two domains are shown in a diagram of the barrier to visual thinking in the design process, Figure 36.

David Ullman (1992) devotes a chapter of his book on the mechanical design process to "The Human Element in Design", in which he presents a model of human information processing, as a simplification of the generally accepted cognitive psychology models. This model has two environments, or domains in our terminology, the "internal environment" and the "external environment", and information processing is said to take place through their interactions. The internal environment is the domain of the human mind, and the external environment is the physical domain external to the human body.

Although the engineering disciplines are particularly interested in objects in the physical world and the forces which act on them, an important tool that is used in engineering design is not a physical tool, but is the human mind. While the study of the human mind will never be the primary focus of engineering, there should be some awareness among engineers of the characteristics and capabilities of this important tool. Ullman describes some of these characteristics in his chapter on the human element, and refers to a famous paper by Miller (1956), "The Magical Number Seven, Plus or Minus Two", whose title
suggests an upper limit on the number of pieces of information that the mind is capable of processing in short-term memory at any one time. Sowa (1984) and Broadbent (1975) argue for the reduction of that limit down to only three working registers, that can each hold one chunk of data ready for processing. As each of these suggested limits are quite small in relation to the large amounts of information that must be generated in a large and complex design project, it would not be inconceivable if these limits of the human mind have an effect on the nature of the design process, which should then be reflected in our descriptive understanding of it.
Chapter 4

THE PROBLEM: UNDERSTANDING DESIGNING

To briefly review the presentation to this point, the thesis problem was initially seen as differing assessments of our understanding of designing. The opposing views ranged from stating that designing is well-defined and a design theory exists, to stating that it is ill-defined and no theory exists. The background context in Chapter 2 pointed out the historical age and strength of design practice, as compared to the relative youth and immaturity of general design theory. It was also suggested that the development of a broad fundamental understanding of design may be hindered by design specialisation, in academia and in practice. In the literature review, we have seen the current state of design understanding, in the form of a great number of existing models of the design process, and have noted some of the models’ structural similarities and their differences. We have also looked at current work in modelling information, and have briefly discussed domains. Let us now look at some critical comments about how designing is currently understood.

Designing has been described as being "ill-defined". In the full context:

"Design, though the object and the subject of our common interest, remains ill defined. Many writers still find it necessary to preface their work with a personal attempt at definition as a context to their own concerns. I am tempted to give my
own definition. ... The difficulty of actually knowing what design is stands in the way of communication about it, and even of constructive thinking about it. Not least it affects our ability to make effective sense of such terms as design research or design method." (Jacques, 1981)

A National Science Foundation planning meeting was described as being not very successful, as:

"there was no agreed definition of 'design' and little unity on the approach to studying it" (Ullman, 1991).

The Design in Engineering Education Division (DEED, 1992), at the 1992 annual meeting of the American Society of Engineering Education (ASEE), considered the issue of a definition of design, and commented:

"During the discussion, the fact that there is no clear-cut definition of design became apparent. Many in attendance had taught design for many years and there were many who had significant industrial experience. However, when discussing "design", we all seemed to have our own definition."

The result of the meeting was the production of a list of action items, the first of which
was:

"Produce a 'consensus' definition of design".

The specific issue of an improved definition of 'designing' is discussed in detail in Appendix C.

In addition to some dissatisfaction with existing definitions, assessments of the current level of design theory knowledge and understanding have been made by saying:

"Design theory research is in the pre-theory stage. There is still a search for the basic vocabulary and building blocks of a theory." (Ullman, 1991).

and

"Compared with many other disciplines, our understanding of design is at a fledgling stage. ... design is in a pre-science phase ... The models (of designing) we describe in the following discussion may overlap in various ways. In some cases the models are simply different ways of describing the same phenomena. We may have to embrace several models to gain a satisfactory picture of design." (Coyne et. al., 1990).

From this discussion of the state of design, Coyne, Rosenman, Radford, Balachandran and Gero proceed to discuss knowledge-based design systems, which are for the most part various experimental computer-aided design tools. The various existing design models
which are discussed early in the introduction are not modified later in the text to provide any better, simpler ways of describing designing.

An unanswered question that arises from the previous quote is:

If it is possible to embrace several models to gain a satisfactory picture of design, why then do we seem unable to describe that picture to anyone else?

This question can be expanded. Why doesn't a satisfactory simple picture of design exist? There would appear to be no theoretical reason preventing the creation of a single simplified picture, that has been composed from a number of existing models.

Regardless of any lack of a theoretical barrier to composing a simple picture of designing, it is not accepted that it has been accomplished. Haies and Wallace (1988) state that from the literature it is evident that:

"Despite a long history of innovative engineering design in industry, and the development of prescriptive methods and models, the engineering design process is still not completely understood.", and

"The design process as it is currently modelled in theory does not accurately match what happens in practice."
These quotations come from the introduction of a paper which reports on the very detailed observation and analysis of an actual 34-month design project. The project used a systematic approach based on Pahl and Beitz (1984). Hales and Wallace concluded that less than half the actual design team work effort was accounted for by steps in the design process model.

With respect to the work of Pahl and Beitz, John Dixon (1991) stated that it embodied the German school of design thought, one of two prescriptions that seem most relevant to current design education. The other prescription was the axiomatic approach of Nam Suh (1990), which Dixon described as seeming to formalize the old KISS adage; Keep it Simple, Stupid. About both of these prescriptions, however, it was stated:

"There is little actual research to support these models."

In fact, Dixon began his paper by stating:

"Engineering design education, especially in mechanical engineering, is adrift. To put it on a proper course, we need to develop a consensus on what constitutes the fundamentals of the field. This can be done by a combination of identifying the fundamentals that underlie the current best product realization practices used at the most competitive manufacturing firms and extracting relevant fundamentals from
the results of past and recent research into engineering design."

His attempt at identifying those best practices and their relevant fundamentals resulted in a list of 15 practices and 11 fundamentals. While the lists cover a broad range of important design topics, the fundamentals are not simply defined or measurable concepts, and there would appear to be some overlapping and duplication. For instance, one fundamental is called New Information and Learning, which could easily be seen as a part of any of the other ten fundamentals. Dixon has defined a need, and it is up to the judgement of others to determine whether he has supplied a sufficient simple, strong, and well-structured classification of fundamentals. Dixon appreciated that some would disagree with his proposed list of fundamentals, and encouraged lively discussion of them in order to make improvements and progress in the area of engineering design education.

Finally, his assessment of the maturity of design research is:

"As a research field, mechanical design is just beginning."

While mere youth is not a problem, the immaturity of design research and understanding would indicate that much remains to be done. A significance of all of the above comments, is that they do not come from uninvolved and uninformed critics, but from design authors who have each attempted to make positive improvements to our understanding of designing by their own thoughtful contributions.
The above comments may be seen as quite general descriptions of the problem of understanding designing. It is not unusual that these authors described the problem in general terms, and could not, or did not, more specifically define the problem, because if they had, the probability of a solution would likely have been greater. Abbé Laugier noted, in 1765, that;

"If a question is well-posed, the solution will be indicated."

This suggests that if a problem can be better defined, then the solution will be more clearly defined. Another consequence of the problem-solution relationship is to caution against a premature attempt to define a problem, which may presuppose that the solution is already known, or has already begun to be limited to a certain range of solutions, perhaps before sufficient investigation has taken place. This caution is relevant in this thesis. The problem to be addressed is not as simple as resolving a difference in views by arguing for or against the existence of a design theory.

Now that our problem investigation has examined the views of those who are concerned about the immature state of design theory, let us turn to a leading advocate of the opposite view. Instead of the expected opposition, with respect to the immaturity of our design knowledge, we find in Hubka (1988) an almost surprising amount of agreement, as he in fact only claims that:
"A design science exists, at least in part, and not fully matured".

With further examination we may also find that Hubka (1987), a leading supporter of design methodology, is not unaware of criticisms aimed at the methodological approach, although he labelled Yoshikawa's (1985) opinion as "extreme", when the latter declared that the known approaches to design methodology are "stories", and not scientific theories. Hubka states that Yoshikawa

"acknowledges that they are certainly instructive and assist the designer directly in making the design process more systematic, but they are not open to objections, because they are reflections of the authors' own experiences, which cannot be questioned."

By this discussion it may be seen that Hubka is retreating somewhat from his claims of a solid theoretical basis for his work, and uses Yoshikawa's objections as support for the lesser claim that even without a basis in scientific theory, existing design methodologies at least are acknowledged to be instructive and can assist in the systematising of the design process.

In fact, Hubka continues by stating:

'The objectives of design science are somewhere between the two extremes of
strict verifiable science and mere helpful stories."

It seems odd that a design science should be described as having objectives that are not strictly scientific, and in making this kind of statement, Hubka undermines claims of a strict scientific basis for his work.

As a result of finding this modicum of agreement on the immaturity of design theory among those who originally appeared to have conflicting views, we may now summarise all of the above comments. There is agreement that there is a low current level of a theoretical or descriptive understanding of the most fundamental aspects of designing. It is lower than is preferred, lower than what may be possible, and lower than a point at which some are comfortable with using the word 'theory' or 'science'.

In addition to this collective low assessment of our current level of design understanding, let us also recall Hales and Wallace's comment on the failure of design theory to match design practice. With respect to practice, it would seem that, from the historical context presented in Chapter 2, we have always had much more ability to practice design than we have ever had to describe a fundamental understanding of it. A widely held belief is that the only way to learn designing is to practice designing (Ullman, 1992). This in fact begins to hint at the real nature of the problem of understanding designing. The problem to be addressed in this thesis can now be stated as the lack of a simple, fundamental descriptive understanding of designing, which is required to match designers' intuitive and
practical understanding of designing.

The distinction is made between the theoretical and the practical understanding of designing, as it would seem that designers know what to do, but do not know how to simply describe what to do. Despite the fact that designing is extensively practised, and is intuitively well-understood by a great many practitioners, what appears to be lacking is a sufficiently simple theoretical description of some fundamental characteristics of designing. These are the fundamentals required to satisfy the need identified by Dixon, and which are also required to satisfy the ongoing search for a basic vocabulary and building blocks of a theory, as described by Ullman.

We will know for certain what the future benefits to design practice may be, that will result from an improved descriptive understanding of designing, only after any improvements are attempted and achieved. An improved theoretical understanding may assist in making absolute judgements of the present efficiency of design practice, and/or judging the potential for improvements to current practice.

This thesis addresses the problem of improving our descriptive understanding of the fundamentals of designing, and presents some results of potential value to the practice of designing.
Chapter 5

THE MODELLING FRAMEWORK

5.1 A SIMPLE DESCRIPTION OF DESIGNING

The problem of improving our descriptive understanding of designing has been identified, and we must now decide on an approach that may reveal some fundamental characteristics of designing. The approach taken is to attempt to describe designing as simply as possible. The reason for taking this approach is that the simplest project can only be described in relatively simple, perhaps fundamental terms. A complex design project can be described in many complex ways, and that complex description can camouflage fundamental concepts with secondary and tertiary issues and concerns. After developing a simple description, it will be checked against examples of actual design practice. It will then be expanded into a modelling framework, Figure 37, which will be checked against existing models of designing, and the design process.

Many existing descriptions of designing have been developed from direct observation of design practice. Let us imagine instead how we would describe designing if we could not directly observe it during the activity, and assumed that it happened behind closed doors, or inside a black box. We can directly observe and compare the before and after states of designing, and describe any inputs and outputs, but we are not allowed to directly observe the activity while it is occurring. With this approach, any observed differences
between the before and after states will be defined as being the necessary result of the design activity.

From the assumption that we can look at the state of designing at two different times, once just before and once just after designing has occurred, we can deduce that designing has taken place between those two points in time. The time that elapses between the start and the end of the activity can serve as a useful measure of the activity, and we know from design experience that designing is not instantaneous, and does take place over time.

The only evidence by which we know designing has taken place, is in the new results that may be observed in the 'after' state of designing, that did not previously exist. From our knowledge of design practice, the simplest result that we could imagine seeing in the 'after' state is a drawing of a new product. This drawing would contain the information that describes a new product. This information would not have existed earlier, in the 'before' state.

Our simple description of designing would now include observations that designing takes time, and produces information that describes a new product.

We may now ask ourselves how this information was produced, and again from our experience, we must conclude that a designer generated the results, as drawings are not self-generating. The drawing may be seen as a physical storage medium for design
information, and the designer is the generating source for that information. We may note that the same information exists in two places. It is in the designer's mind and is recorded in the drawing. This leads to a classification of two domains of the same information, the cognitive domain of the designer, and the physical domain of the drawing. Both of these domains are necessarily involved in any complete design project. If the information exists only in the designer's mind, then there is no external evidence of any design activity, and conversely, for design information to just appear on a drawing would be miraculous.

Our simple description of designing now includes the passage of time, and the generation and recording of information which describes a new product. That information exists in at least two domains, the internal cognitive domain of the designer, and the external physical domain.

The three identified fundamental characteristics of designing, Time, Information, and Domain, will now be checked against examples of actual design projects.
Comparing the Simple Description of Designing and Actual Practice

The three fundamental characteristics that have been identified, will now be confirmed for their existence in two examples of actual design projects. These projects are described in detail in Appendices A and B. These projects represent a typical mechanical engineering project and an industrial design project respectively. Other than the fact the complete design project history was available in both instances, these project examples were not specially chosen.

The Creme-Lite mixing and storage tank.

The process of designing a Creme-Lite mixing and storage tank is described in an engineering case study in Appendix A.

The design project took place over a period of time, as evidenced by the June 8th date of the quotation, and the July 18th date of one of the final drawings.

A considerable amount of design information was generated during the project, information about the storage tank, its function, features, components, how it interrelates with the creme-lite, the water, the steam, and even the rules for operation of the tank.

As this was a more complex project than the described simple project, the design
information was generated and stored in more than the minimum two domains. George Crassa was the principal designer, and by definition would have developed and possessed the information about the tank in his mind, and the same information about the tank was recorded in a second domain, the physical domain of the product drawings. Harry Anson, the draftsman who undertook the detail design, must also have had some personal knowledge of the tank and its requirements within his mental domain, to allow him to generate his contribution to the design information, which was then also recorded in the physical domain. The mind of Webb, the plant engineer at G. West Ltd., represents a fourth domain where design information necessarily can be found, as may be deduced from the awareness of the project that Webb must have had, considering he set out the requirements and monitored the design project. Others, such as the workers who added bracing to the legs of the tank during its manufacture, also played minor roles in contributing to the ultimate design of the tank, and to have made their contributions, it must also be assumed that they both possessed and generated some information about the tank within their own cognitive domains.

Hospital bedside computer terminal design project.

Appendix B contains the description of an industrial design office’s involvement in a hospital bedside computer terminal design project. The description is in the form of a transcript of a conversation between Scott Gibson, the designer/owner of the industrial design office, and the author.
With respect to the first fundamental factor of time, the total time taken for the project is not discussed in the transcript, although it may be deduced that the project did take time, and likely considerably longer than 16 weeks, which was the mentioned availability of the LCD screen. It can also be noted that the original time phases of the project were considerably re-defined in the middle of the project, as there was a major readjustment that included changing the makeup of the design team.

With respect to the second characteristic, information, a considerable amount of information was generated during the project, and throughout the transcript reference is made as to the various kinds and amounts of physical information results that were produced, in various forms, from thumbnail sketches to working prototypes.

As well as existing in the physical domain, in intermediate and final results, design information was generated and stored in the cognitive domain of each person involved in the design process. These people include those at Scott Gibson Design, Digital, the hospital consortium, the touch-screen designer/suppliers, and the mold makers. They were all aware of large portions of the total design information. It is interesting to note that no single location or domain contained each and every single piece of design information that was dealt with during the project. Each individual possessed significant amounts of the design information, relevant to their contribution. This would significantly overlap but may not completely duplicate that which another individual possessed. All the information considered is not available even in the physical domain, as the collected
sketches, physical models and drawings only need to contain those choices which were accepted. All the other choices which were considered but then rejected in the cognitive domain of any person, would not necessarily be recorded in the physical domain.

The Modelling Framework

From the simple description of a design project, we have identified three fundamental characteristics of designing. These have been demonstrated to exist in two examples of design practice. The three characteristics of Time, Information, and Domain will now be used as the dimensions of a modelling framework. This framework is presented in relation to prior models of designing, and it provides a context for relating prior models to each other. The three dimensions are suggested to be independent, and fundamentally necessary to designing. They are not the only dimensions in which designing could possibly be modelled. These three particular dimensions have been chosen, however, because they describe designing simply, and they interact to allow the modelling of a very broad range of design activities and results. The simple strength of these dimensions lies in their independent but inter-related nature.

It will be shown how 'designing' can be modelled with respect to each of these dimensions individually, in various pairs, and all three together. They are discussed first as simpler singles and pairs, starting with the dimension of Time. This starting point is
convenient in that it establishes the connection to activity-sequence design process models.
5.2 TIME

The Dimension of Time and The Activity-Sequence Model

Design projects take place over time. Describing what is done during that time is the concern of the activity-sequence design process model. The previous simple description of a design project discussed a single activity; designing. Activity-sequence design process models operate with the assumption that designing is not made up of a single completely homogenous activity, but a somewhat heterogenous one composed of many different and separately identifiable sub-activities. Process models take the total design activity, and split it into sub-activities. If the overall activity of designing takes place over the total time of a design project, then sub-activities of designing must occupy fractional amounts of that total time.

The fact that time passes during a project should not by itself be a cause for disagreement. The total time taken by a design project can vary greatly, however, from minutes to years. Any identifiable minimum and maximum bounds are believed to lie between zero and positive infinity. These bounds cover a very great range. Any two design projects could fit within the range, but cover greatly varying amounts of time. Because of this possible variance among projects and their time-scale, differences of opinion may arise when the total activity is arbitrarily broken up into a certain number of sub-activities, steps, stages, or phases, with no apparently strong basis for choosing a
particular number of activities, or their size on a time scale. Heuristic design process models have had as few as three steps, or as many as 229, or various numbers in between, and most models also allow an infinite amount of repetition, or cycling. It is believed that the differences among design process models may never be resolved, as the 'best' number and size of activities in the 'best' sequence may be very project dependant, and in current models appears to be only weakly based on individual or corporate preference, or other anecdotal evidence.

While the issue of a best process model is not likely to be resolved, the typical nature of the models may be examined in order to facilitate making practical improvements where possible. As discussed, present design process models have concentrated on the sequence of design sub-activities. (Sub-activities will also be simply referred to as activities, by shifting the frame of reference). If we look into the structure of a sequence of activities, as in the typical design process model, we can find the basic unit of A then B, Figure 38. This unit is composed of two boxes joined by an arrow. It indicates Activity A, as the first box, is to be performed first. Once Activity A has been completed, the arrow then indicates proceeding with Activity B. When multiple units are strung together, a sequence is formed which indicates Activity A is followed by Activity B which in turn is followed by Activity C. In these larger patterns, it is also common to find additional arrows, which represent the feedback of information or partial results. These feedback arrows, or cyclic loops, return to earlier boxes, and indicate that Activity B may at times be followed by Activity A, or that Activity C may also sometimes be followed by
Activity A or B, in a return to earlier activities in the process. This larger pattern including feedback is shown in Figure 39. A typical example of this kind of design process model is Shigley’s, Figure 21, in which every box except the last shows iteration loops that allow the return to prior activities, steps, stages, or phases.

The wording of the last sentence was deliberately chosen to include four different names for the boxes, to point out a part of the nature of the boxes-and-arrows design process model, which is the difficulty we find in deciding what to call the boxes. While we may be unsure of the differences between the use of labels such as activities, steps, stages, or phases, it is suggested that they are all similar in that they are all labels for periods of time. All four can be defined by starting and ending points in time. In a typical design process model, each of these defined steps is generally assumed to take place one at a time, and follow each other in time, according to some sequence or order. Differences in the common usage of the four different labels are based on quantities of time. Different labels often refer to different scales of time, or orders of magnitude.

This comment on different time scales of design activities raises a criticism of Asimow’s (1962) claim of modelling both a horizontal and a vertical dimension of the design process. When these dimensions are more closely examined, they are seen to be the same, and model the design process in the single dimension of time. It appears Asimow has in fact modelled two cycles, or sequences of activities, of different scales, in the single dimension of time, where the sequences contain activities which represent either
a coarser or finer set of divisions in time. The sequence containing the finer divisions in time is cyclically repeated within the other coarser sequenced cycle of activities, but both represent a similar progression with respect to time.

**Time and Results**

The structure of the design process model has been described as one which relates a sequence of boxes, which are labelled activities in time. These activities can also be called steps, stages, or phases. Design process models do not always model just activities however, but may sometimes also model results, as in Eekels and Roozenburg's model. Figure 26.

In this model, between each labelled box is an intervening label, which describes a result. Each result serves as both a described output of a prior activity, and a necessary input to a subsequent activity. The model begins with the label 'Problem', which is assumed to be supplied to the process, and is a necessary input to the first activity, 'Analysis'. The output result of the first activity is 'Requirements', which is also an input to the next activity of 'Synthesis', and so forth.

It should be noted at this point, that by including design results in the process model, something of a different nature is being introduced into the model. Results are not the same as activities, and have a different relationship with respect to the dimension of time.
We will continue to discuss results as they relate to the typical design process model and the dimension of Time, although results more properly belong to the Information dimension of our modelling framework.

With respect to expanding the design process model to include design results, it is suggested that the following aspects should be explored:

- The nature of design results.
- The differences between design activities and results.
- Modelling differences between activities and results.

The Nature of Design Results.

It is suggested that all design results are similar. This may not be apparent upon quick examination, as design results are also quite different. They take a variety of forms, including drawings or blueprints, briefs, files of computer data on magnetic storage media, specifications, sketches, physical models, slides, video, or verbal presentations. Despite this broad variety, they can all be considered in a similar manner, as information. Bruce Archer (1965) was possibly the first to point this out, when he listed a range that included eight means by which a design idea may be expressed, from words, symbolic logic, and sketches, to simple models, working analogues and prototypes. He describes each of these different forms of design results, as being merely different representations of a
design idea. In this context, 'idea' and 'information' are used interchangeably. In order to visualise the similarity of design results as information, the information must be mentally separated from the medium in which it is expressed. For example, a drawing may be seen as design information plus paper and ink, and a solid model as design information plus wood and paint. The paper, ink, wood, and paint are just raw materials, and are the media which support the information, as air is the medium supporting sound information. It is the information component of the drawing or solid model that adds value to the raw material of each one. This kind of decomposition of the external physical results of a design project, can be similarly applied to the internal cognitive results. Cognitive results, or ideas, are made up of design information supported by the biological medium of the mind. The suggested conclusion is that all design results may be simply and similarly classified as information.

As example, in Appendix A, the information that describes the 5 foot diameter of the Creme-Lite mixing tank was recorded on paper in the case study text, was also shown on the drawing, and could easily have been represented on a scale model of the tank. The same information could also have been obtained from a measurement of the tank after manufacture. The practical caution with multiple instances of what is intended to be the same information, is that one must of course always be careful to check for correspondence and accuracy. Within the limits of acceptable accuracy, the information is intended to be multiple copies of the same information.
The Differences Between Design Activities and Results.

Design activities are typically described as sequential sub-activities of the overall design activity, to be performed singly, one activity following another. This implies that as the second activity is being undertaken, the first activity is considered to be set aside or finished, and is no longer current. It is suggested that activities can be described in essentially digital terms, in that an activity either is currently being performed, is in the 'on' state, or is not currently being performed, is in the 'off' state. There is also no particular quantity of an activity associated with these on and off states. The activity either completely exists or it does not.

On the other hand, it is suggested that design results are very different from design activities. Design results are not expected to be achieved in digital blocks, and once achieved, they are not expected to be discarded, or turned off. Design results are often gradually built up, and are pieced together and accumulated over time. Design results are also not expected to be forgotten after they are achieved. They are expected to continue to exist, and are often necessary inputs to later activities. A measurable quantity may be associated with design results, in that a certain quantity of information can be described as having been achieved at a certain point in time.

A demonstration of this difference between design activities and design results, is to imagine what exists at a certain dormant period in the middle of a design project, say
during a coffee-break. During that break, if an outside observer was to check on the current status of design activities and design results, it is expected that the observer could report that no design-related activities would be said to currently exist, yet every design result achieved to date would be said to currently continue to exist.

Modelling Differences Between Activities and Results.

It is suggested that the discussed differences between results and activities can, and should, be accurately reflected in how they are modelled. We have already seen how design activities can be modeled in a boxes-and-arrows fashion, in which each activity is assigned to a box, and the sequence of connections to other activities is shown by arrows. Although a design process model with its feedback arrows has the appearance of a two dimensional model when drawn on paper, it is most often a linear one-dimensional model, in time-sequence, or order, which for simplicity has been folded back on itself. As the arrow of time points forward to the future, a process model could be stretched out, with the appropriate cyclic repetition of its component activities, into a linear model in the dimension of time. This can be shown as in Figure 40. Although the activity in Figure 40 can be also be shown as in Figure 41, in which we have emphasized the 'on' and 'off' states of the activity, the models are essentially the same. The vertical dimension adds little extra utility to the model.

There are other, perhaps more useful ways to use the second, vertical dimension of the
model, as shown by the addition of a results dimension, as in Figure 42. This model shows the results produced in association with a given activity. As the results are produced over the course of the activity, they are shown as a ramp shape, in contrast to the step shape of Figure 41. The continuously accumulating quantity of information that results from a design activity is modelled in a continuous ramp, not necessarily linear, that shows an increase from zero to the full quantity of information over time.

The vertical axis is a measurement of the quantity of information that results from a design activity. Value judgements could be superimposed which would sub-divide the total information quantity into various quality categories, principally into that information which has value and that which does not. This could be particularly useful in modelling a brain-storming activity, for instance, which would show a large total quantity of information being produced in a short time, with only a small percentage which is ultimately judged to be of valuable quality. While this possible sub-division it is of great interest, for the sake of simplicity this topic of information quality will not be further explored. The models currently being discussed, and as shown in Figures 42 through 48, describe design results in terms of quantity only, and not of quantity and quality.

The start and end points shown in Figure 42, correspond to the start and end points of the design activity which is producing the result. What is of particular interest is that once the full result is achieved, i.e. at the end point of the activity, the quantity of design results continues to be modelled at its current level, and does not drop to zero in the way
that a model of an activity does. This continuity beyond the end of the activity is suggested to be the significant difference in accurately modelling design results, in comparison to the modelling of design activities. This important difference between modelling activities and results will be utilised in the following Time-Results model.

The Time-Results Model.

This model has two dimensions. Time is modelled horizontally, and results are modelled vertically. The nature of the model suggests that for any design activity, there should exist a corresponding design result, representing an increase over prior results. The units of time can be minutes, hours, days, weeks, etc., all of which belong to an overall system. The units, and a system, for measuring design information results have not been well-developed. Although some possible candidates for a primitive unit of information are a 'bit', or a 'chunk', the development of a complete practical system to measure design information both quantitatively and qualitatively has not been explored to a sufficient depth to be usefully discussed at this time. Although such a system has not been developed, it should be of significant importance in any future evaluation and measurement of design process efficiency.

For the present, quantities of information can be discussed on a macro level, such as a number of drawings, or a number of bits or files on a computer disk. Ullman (1992)
approached this issue on the broadest level, in terms of the total amount of information required in the design of a new automobile. He presented a comparison of the lengths of time it took American and Japanese companies to design a new automobile, from concept to production, during a comparable period in the early 1980s. The Japanese took 3.5 years to develop a car while the Americans took a little over 5 years. It is assumed in this comparison that similar cars were compared, and that a similar amount of information is required to describe each car and its associated production and manufacturing information. The Japanese were not only quicker, but the cars they produced were judged to be of higher quality than the American ones. This represents a rare discussion of measurable design process efficiency, and it is on a very simple and large scale. As this example is seen as a valuable comparison between two different approaches to the design process, it is suggested that this method of efficiency analysis shows valuable promise which should be further developed, through better measurements of the quantity and quality of information required for given design projects.

Discussing information in macro terms, as a total quantity, leads to an examination of some constraining bounds of the Time-Results model. If it is accepted that both Time and Information are positively cumulative, any measurable quantities will lie between zero and positive infinity. Within these ultimate limits, the progress of Time is always increasing, and barring some form of destruction of Information, it too can only progress in positively increasing quantities. This adopts the conventions that the arrow of time points towards the future, and that even new information which may contradict or negate
prior information is still classified as additional information. In mathematical terms, the absolute value of any quantity of information is always a positive quantity; in colloquial terms, it is suggested that you can never learn less about something, only more. The positively increasing nature of both dimensions within the bounds at zero and positive infinity, has the effect of placing the modelling of design in the first quadrant of a Time-Results model. This is consistently inclusive of the practical observation that a design project starts when the pencil hits the paper, and only ends when the product is obsolete.

A Time-Results model can be shown as in Figure 43, which models a design project as it occurs between points A and B. The design activity takes places between time Ta and time Tb, and the achieved design results are shown as the difference between results Ra and results Rb. The design activity has generated some information results, so that Rb > Ra, and some time has elapsed, so that Tb > Ta. The quantity of time is (Tb-Ta), and the quantity of results is (Rb-Ra). A coarse measure of the mean efficiency of the design activity, in terms of achieved results over time is (Rb-Ra)/(Tb-Ta), which is the slope of the line from A to B. A more time efficient design activity would be diagrammed with a steeper slope than that of a less efficient design activity.

The Time-Results model presents design activities and their results differently than the way they are presented in the traditional box-and-arrows model. This difference can be useful in re-evaluating the boxes-and-arrows models, and judging which boxes-and-arrows example best handles certain details. Both bad and good examples can be found.
In the first example, the box labelled 'Conceptual Design' in French's process model, Figure 9, is examined, to see how it would be shown on a Time-Results model. It is quickly seen that it cannot be easily and directly modelled. Questions are raised. Is 'Conceptual Design' the name of an activity, a result, neither, or both? If 'Conceptual Design' is neither, and is merely the name of the box, what are the names and natures of both the corresponding activity and result? If the answers to these questions are not clear, and it is suggested that they are not, then this label is not as clear as it could be, and may be judged to be poorly chosen.

Another example shows how a different model can be much more easily shown as a Time-Results model. A process model such as Eekels and Roozenburg's (1991), Figure 26, appears to be more carefully conceived than was French's, if judged on the basis that each stage has an explicitly named activity and an explicitly named result. It is suggested that a better design process model is one which has well-classified design activities, which will each have clearly specified input and output results.

Generating Results

One assumption on which the Time-Results model is based, is that design results are generated during a design project. While this must be a correct assumption, as a design project with zero results is a trivial case, our understanding of the design process may be improved by exploring and explaining the mechanisms by which it is possible that results,
in the form of information, can be generated during a design project.

A modelling technique that examines the generation of information is one that looks at individual design steps or activities in terms of an Input/Output model as in Figure 44. This model shows an individual design activity as the labelled box, with its associated input and output results as arrows. This model is similar to the basic unit of the activity-sequence process model (Figure 38) and differs primarily by the placement and labelling of the arrows.

When this model is used as in Figure 45, to illustrate a logical thinking activity such as deduction, it illustrates the generation of information, and points out an interesting property of information that matter and energy do not share. Whereas energy and matter would be conserved in a similar diagram, this model shows a process by which new information can be generated. In deduction, information about a specific instance, or Case, is combined with the information contained in an applicable general Rule, to deduce, or generate, additional information. This additional information is the Result. The following syllogism shows this.

Case:        Socrates is a man.
Rule:        All men are mortal.
Result:      Socrates is mortal.
Figure 45 diagrams the activity of deduction, and shows that the Case and the Rule are conserved as they pass through the activity box unchanged, and that a Result has been generated. This Result represents new information that was not consciously known prior to its generation. While it is apparent that the Result has had its origins embedded in the selected Case and Rule, for practical purposes the Result can be seen as newly generated information. It is suggested that the very purpose of labelling 'deduction' as an activity is in fact to understand this process of generating a new result. It is only through the activity of deduction that otherwise unknown results are deduced, or are brought into conscious awareness or existence.

Deduction is not the only process, or activity, by which design information can be generated or even acquired relative to a specific design project. Design information results can be generated by any logic operation such as deduction, induction, and abduction, as well as by any other activity such as observation, recognition, and research of sources in the external world, and/or by recall of information from a designer's internal memory of prior knowledge and/or experience.

Note that in the Time-Results model we are modelling information that is associated with a particular design project, at the time at which it is consciously associated with that project. This makes sense in practice as the existence of some information in the world can be of no significance to a design project, if it remains unknown within the context of that design project. The moment at which the piece of information gains significance,
is only at or after the moment at which it becomes known to the project, and not before.

Modelling an Innovative Activity

The idealised case portrayed in Figure 46, shows what would be considered an innovative design. The design activity begins with zero information, with the figurative 'blank sheet of paper'. All of the final quantity of design information is generated during the design activity. No large portion of it is available at the start, as it is in a re-design activity. Although it can perhaps be successfully argued that a design project does not yet exist if the initial quantity of information was identically zero, it is suggested that the lower limit of initial information approaches zero. Even if it is allowed that some initial need must exist, the lower limit on the amount of information that comprises a need may be near-zero. In recognition of the approach of this limit, for simplicity's sake in the idealised case, an innovative design can be described as beginning with zero information.

Modelling Input Results

In contrast to the innovative design project activity, an activity which has a substantial quantity of initial input information would be modelled as in Figure 47. A figure of this shape would be used in modelling an overall design project which has a large given input, such as the re-design of a given product. It is expected that the information that is already known about the existing product represents a major portion of the input
information in a re-design project. This diagram is also characteristic of any particular design sub-activity which requires a necessary input. The name and nature of the input information required for a non-innovative design activity should be clearly described. In a sequence of connected design activities, the identified output results of a prior activity may also be the input results of the subsequent activity.

The difference between the shapes of these two models, Figures 46 and 47, forms the basis of an important line of questioning regarding input results, that could be posed to the authors of conventional design process models. It is not clear, even with an apparently well-crafted design process model such as Eekels and Roozenburg’s (1991), Figure 26, exactly what relationship exists between the various partial results that make up a total project. There are three distinct possibilities:

Each partial design result is independent of the previous results.
This would mean that each activity is completely innovative, and would appear as in Figure 46 with no prior information required as input. The overall model would appear as in Figure 48 (a).

Each partial design result is completely dependent on earlier developed results.
This would mean that each stage would have the shape of Figure 47, and each design result would be a necessary input to the next activity and would be fully embedded in the subsequent result. The overall model
would appear as in Figure 48 (b).

Each partial design result is partially dependent on prior results. This would mean that subsequent stages would also have the shape of Figure 47, although only some portion of the results of previous activities would be required as necessary inputs to following activities. The overall model would appear as Figure 48 (c).

A composite variation would combine elements of the above possibilities.

Summary

Modelling designing with respect to the dimension of time has been examined. Conventional design process models split the activity of designing from start to finish into a sequence of sub-activities. These activities are most often modelled sequentially in time. Some process models also include the modelling of the design results that are a product of each activity. Design results have been seen to have a different nature than design activities, leading to the recommendation that they be modelled differently. The Time-Results model has been shown to be a two-dimensional model which deals with the differences between activities and results, and one which can be used as a tool for examining the interrelationship of design activities and design results.
5.3 INFORMATION

The Information Web

In the previous section we looked at Time; the first of our identified fundamentals of designing. We saw how design process models were primarily concerned with modelling sequences of activities in time, and some also included the modelling of design results. The nature of design results was examined, and we saw that they were quantities of information, which are not modelled with respect to time in the same manner as activities. This necessitated a second dimension, which was utilised in the Time-Results model. In this section we look at Information; the second fundamental characteristic of designing and another dimension of our modelling framework.

The measurement of information was briefly discussed in the previous section. Fairly rough large-scale measurements are possible, but a cohesive, precise, and practical system of measurement of quantities of design information is not known to exist. A system of information quantity measurement could allow measurements of the efficiency of a design process, by measuring the quantity of information achieved versus the quantity of time consumed. This could be useful for evaluating various design process models, and/or their component activities. The only caution anticipated is related to the quality of the design information. The value of knowing the efficiency of producing a certain quantity of information could be reduced somewhat if the quality of that information had a large
variance.

The identification of the dimension of Information, and its use in the Time-Results model in the previous section, raised some useful questions about existing design process models. These questions involve the care with which various design activities and their corresponding results have been classified in these models, and in their sequences of activities, whether there is full dependence, partial dependence, or no dependence between subsequent partial results. Answering these questions will improve our understanding of design process models. We now leave design process models, and will continue by concentrating on Information alone, independent of Time.

The literature review presented some models and methods of representing information, from semantic networks to cluster diagrams and entity-relationship diagrams, that all go beyond the common-place use of conventional written text and pictures of objects as methods of recording and displaying information. In this section we explore those models and develop some additional ones that hold particular promise as design information tools. This will demonstrate the validity of choosing Information as the second fundamental characteristic of designing and as a dimension of the modelling framework.

Conventional text is a linear sequence of words and sentences, with a start and a finish. Other methods of displaying language information may use words and concepts in interconnected diagrams that have no defined start or end. Typical examples of these
types of diagrams were shown in the literature review, Figures 28-31. It was noted that the spatial relationships of the elements in the diagrams may not provide any additional meaning beyond the assumed connection shown by the lines and arrows, which in many of these diagrams, are not labelled, leaving their precise meaning somewhat unclear.

The more complex diagrams in the literature review may show much of a large topic. These diagrams contain the component concepts of a certain topic and their interconnections. On a simpler scale, Geoffrey Leech (1974), in the field of semantics, shows how individual sentences can be diagrammed. In his diagrams, every word or phrase is diagrammed in one of two ways. They are either a circular node, or a connecting link. The nodes represent arguments, and the links represent predicates. These two classes of diagrams, the complex topic-level, and the somewhat simpler sentence-level, are of two different scales. There is the structuring of information about a whole topic in the first case, and a detailed structuring of individual sentences in the second. Combining the two classes would result in a detailed diagram, or connected graph, which could not only cover the whole of a topic, but could do so in as detailed a manner as necessary. The model developed in this section, the Information Web, is just such a combined diagram. It covers the whole of a design project, yet can also show the details of the project.

An Information Web is constructed by connecting many individual sentence level diagrams to form a single more complex diagram. The sentence level diagrams are similar to Leech's diagrams. Simple sentences describing any aspect of a design project
can be diagrammed. These diagrams show individual concepts and details of the design project and their interrelationships, and the diagrams are the building block units of the single larger one. The unit diagrams are connected at common nodes. These common nodes are those concepts or details of the project which have appeared in more than one sentence-level diagram. As each node will appear only once in the overall diagram, multiple unit diagrams that refer to the same thing become connected to each other through connecting or overlapping all the references to the common described concept or detail. This overlapping stack appears in the diagram as a single occurrence of the node, with many connecting links radiating out from it.

An example Information Web model of an actual design project is shown in Figure 49. This model is of the engineering in Appendix A. This example shows the potential of the model to capture the content and relationship information which comprises the results of a design project.

From Leech’s work it may be conjectured that the potential exists, with sufficient development of diagramming techniques, to diagram virtually any subject describable by language. This potential ability to diagram any subject is a feature used in the Information Web, which is intended to capture design project information in a single format. The Information Web is a modelling tool which is only concerned with information, and not with the activities which may be required to produce the information. It is a tool which can display, and allow the review of, the total amount and content of
the design information achieved to date, and the relationships between various pieces of information.

The example shown is a diagram of the information content of only the first few pages of the design project case study. It is suggested that similar manual recording and modelling of the information for a large complex project could easily become a very difficult chore. The application of some current advances in database modelling could reduce this difficulty and could play a significant role in further development of this kind of model.

The entity-relationship approach to database modelling and design, introduced by Chen (1977), is an information modelling approach which can model a wide range of entities, usually real-world objects, and a similar wide range of relationships between entities. The entity-relationship approach, and the computer aided software engineering (CASE) tools that have been developed from it and for it, demonstrate the ability and utility of the computer to model information in this way.

It is suggested, following development of the necessary modelling techniques and tools, that for any design project, a complete information web model could be built, maintained, and displayed using computer technology, that would capture, in a common format, every current piece of design information that is describable by language. This web would form a single, large, interconnected network of entities and relationships, and would provide
a current model of the information results of the design project.

It is believed that such a model, by storing design information in a single modelling format in the electronic domain of a computer system, would be useful throughout the project. It could be particularly useful early in a design project. Early in the project it would be used for initial information gathering and storage, and for exploring and testing the as yet unknown relationships among various pieces of the information. This exploration and testing of relationships would continue as each new piece of information is observed, generated or discovered. The model could also be particularly useful for teams of designers, to have a collective common storage and display model for all of the design information for a given project.

The utility of the Information Web is enhanced by the ease with which it may be understood. It is suggested that it is easy to understand because, like the entity-relationship diagram, it is a connected graph very strongly based on language. Comments on the ease of use of the entity-relationship diagram should also apply to the proposed Information Web, due to the structural similarities between the diagrams. Various authors in the field of database design have commented on the ease of understanding the entity-relationship type of diagram, including Chen (1977), who stated that the "enterprise schema", (a model of the company or enterprise), "expressed by the entity-relationship diagram is more easily understood by non-EDP (electronic data processing) people", and Teorey (1990), who noted "The overriding emphasis in ER (entity-relationship) modelling
is on simplicity and readability."

The possibility, and the utility, of adapting entity-relationship modelling for use as an Information Web tool in a product design application, can be extrapolated from the following statement by Teorey (1990):

"The goal of conceptual schema design, where the ER approach is most useful, is to capture real-world data requirements in a simple and meaningful way that is understandable by both the database designer and the end-user."

To paraphrase Teorey's statement, it could be suggested that:

The goal of design, where the Information Web model is most useful, is to capture real-world requirements, future product possibilities, and their relationships, in a simple and meaningful way that is understandable by both the designer and the client.

While this thesis has not fully investigated existing database design tools, it is expected that this avenue could hold much future promise to a broader range of designers. It is suggested that a similarity between database designers and designers in general is that all are trying to develop information structures which match and describe reality. Some specific differences are that database designers are trying to discover an information
structure which describes part of the real world, and which can then be used to support a database for handling future information about that part of the world, while a product designer, for instance, attempts to develop an information structure that describes the needs and preferences of part of the real world as well as the attributes of a possible future product that can satisfy those preferences, so that part of the detailed information structure can then be used as the blueprint for manufacturing a product.

The Information Web and The Time-Results Model

In comparing the Information Web with the Time-Results model discussed earlier in the thesis, it is apparent that while the Information Web has the capability of displaying the connections between a great many pieces of detailed information about entities and their relationships, the Time-Results model easily deals with a smaller number of distinct activities and their output blocks of design project information. The Time-Results model is a top-down structuring of a complete design project, and like the activity-sequence models to which it is related, is probably most useful for a single level of breakdown of the design process. This breakdown would likely result in a relatively small number of pieces, possibly in the range of 3 to 20 categories of activities and corresponding results, as in the range of typical design process models.

The Information Web model is unlike the Time-Results model in that it makes no attempt to deal with time. Without adding something extra to the model, the only way to capture
time in an Information Web is to examine the changes over time between an older copy and a more up-to-date version of the model for a particular project. In this regard, the Information Web is not well suited to act as a process planning tool, but rather as an information storage and display tool. The quantity of information contained in an Information Web will increase over time, but the nature of the information will likely change somewhat, as the project moves from abstract concepts through to including more concrete details.

Design process models and the Time-Results model are structured around sequences of activities, which are structures in the dimension of time. In these models, any related categories of results are also structured in time. In contrast, the Information Web is most easily structured in the dimension of information, not time. Divisions that cut across the information dimension can run parallel to a time-line. By running parallel to the time dimension, and perpendicular to the information dimension, these divisions can cut the total design result information into sub-results, or categories of partial results, that are independent of time. Each category can be maintained over time, and the information in it is simply expanded over the life of the project. The categories need not change, only their size.

Separating design results into categories which are independent of time, can be seen in the Creme-Lite mixing tank example, in both the case study and the example Information Web of the project. First, it may be noted that the case study is divided into many
sections which describe various partial results of the project, such as the pressure vessel
design, the fluid dynamic drag, etc. These are separate categories in a structure of results,
and are not classified or structured according to the various activities that would have
been required to generate, verify, and record these results.

Second, a structure of information results can be seen in the Information Web diagram
of the Creme-Lite tank, Figure 49. The diagram reflects a split in the total information
of the project. The left side of the diagram contains information which describes the
tank, and can include any details of its material, features, dimensions, etc. The right side
of the diagram displays information which describes the context for which the tank is
being designed. It is a description of the problem, and describes the factors which
constrain the design of the tank. It includes information describing the food product to
be handled, the companies and individuals involved, budgets and schedules, the water and
steam which will be used to cool and heat the tank, etc. Connecting the two sides of the
diagram are the relationships between the tank as the solution and the context as the
problem.

The Prime Interface of an Information Web

While an Information Web is a single graph, or network, of entities and relationships, the
web can be split or structured. The following describes a split along a prime interface,
which is suggested to be the most important and useful split of the design information.
It is noted that topologically, a single split creates two parts. For instance, to split the web so that one portion contains information about the 'function' of a product, also creates a portion of the web whose defining characteristic is about 'not-function'. Similarly to split off a portion concerned with 'cost' creates a 'not-cost' remainder. Any split, or interface, has the property of defining both sides of the interface.

The suggested prime interface is a split of the Information Web so that one section describes the 'product'. By default, the other section describes the 'not-product'. Note that the web is split across linking relationships, and does not cut through any entity nodes. This split into 'product' and 'not-product', is a useful one. The so-called 'not-product' section is that important part of a design project which describes the context, or situation for which the product is being designed. Although it conceivably represents the rest of the universe, in practical terms it represents only that part of the universe that has relevant importance in the project. It may be thought of as that part of the universe belonging to the 'near-neighbourhood' of the interface, and hence of the product. This split between product and context, and the resulting interrelationship across the interface, is in accordance with Alexander's (1964) description of the whole of a design project as an ensemble.

Alexander's ensemble is composed of two parts, a form and its context. His reasoning for the split in the ensemble is as follows:
"It is based on the idea that every design problem begins with an effort to achieve fitness between two entities: the form in question and its context. The form is the solution to the problem; the context defines the problem. In other words, when we speak of design, the real object of discussion is not the form alone, but the ensemble comprising the form and its context. Good fit is a desired property of this ensemble which relates to some particular division of the ensemble into form and context."

The suggested split of the Information Web matches Alexander's, describing:

the Information Web as the ensemble,
two sections of it; the product, or form, and its context, and
their inter-relationship, or goodness of fit, across the dividing interface.

Herbert Simon (1969) joins Alexander as another author who has described this fundamental division of a product and its context, in characterising "The Artifact as 'Interface'." He uses the example of a clock, and states:

"An artifact can be thought of as a meeting point - an 'interface' in today's terms - between an 'inner' environment, the substance and organization of the artifact itself, and an 'outer' environment, the surroundings in which it operates. If the inner environment is appropriate to the outer environment, or vice versa, the
artifact will serve its intended purpose. Thus if the clock is immune to buffeting, it will serve as a ship’s chronometer. (And conversely, if it isn’t, we may salvage it by mounting it on the mantel at home.)"

Simon adds to the discussion an artifact’s 'behaviour'. Where an artifact’s inner environment is often hidden, a typical user can only make external observations of an artifact’s behaviour, which is its output reactions to various inputs. The artifact’s behaviour can then be described as that which crosses the interface between the inner and outer environment. On designing, Simon writes:

"Description of an artifice in terms of its organization and functioning - its interface between inner and outer environments - is a major objective of invention and design activity."

The following two examples provide additional current support for this fundamental split in design information. They also provide some evidence that, years later, Alexander’s warning, that designing is not only about the product, but is also about its context, and their inter-relationship, has not been universally heeded.

In a March 27, 1993 news story in the Globe & Mail, which announced Louis Gerstner’s appointment as chairman and CEO of IBM, the company was described as being "caught off guard in the eighties by a shift in market demand for smaller, more powerful PCs."
The article states that Gerstner has made it clear that IBM's future hinges on being more responsive to its markets, and quotes his statement; "What IBM has to do is get back in touch with its customers." In contrast to his views, the article also notes that "shareholders and customers have already voiced concern about Mr. Gerstner's lack of technological experience." The article points out two areas of focus, technology and the customer, and reveals that the CEO and the shareholders appear to either focus on one or the other. Neither party discusses both, and neither party directly expresses a concern over a potential third area of focus, the goodness of fit between the product and the customer.

Similarly, in the March 1993 issue of The Atlantic Monthly magazine, there is an article on bad product design titled "The Complexity Problem", by John Sejgalwick. The article opens with the declaration that:

"It is becoming increasingly clear that the comfort of a good fit between man and machine is largely absent from the technology of the information age."

The previous discussion points out the importance of this prime interface between form (or product) and context. Because of its importance in defining the product, it would seem likely that this interface in the design project information should be defined early in the project. There is however a major caveat, expressed by Alexander (1964).
"We must also recognise that no one division of the ensemble into form and context is unique. Fitness across any one such division is just one instance of the ensemble's internal coherence. Many other divisions of the ensemble will be equally significant. Indeed, in the great majority of actual cases, it is necessary for the designer to consider several different divisions of an ensemble, superimposed, at the same time.

Let us consider an ensemble consisting of the kettle plus everything about the world outside the kettle which is relevant to the use and manufacture of household utensils. Here again there seems to be a clear boundary between the teakettle and the rest of the ensemble, if we want one, because the kettle itself is a clearly defined kind of object. But I can easily make changes in the boundary. If I say that the kettle is the wrong way to heat domestic drinking water anyway, I can quickly be involved in the redesign of the entire house, and thereby push the context back to those things outside the house which influence the house's form. Alternatively I may claim that it is not the kettle which needs to be redesigned, but the method of heating kettles. In this case the kettle becomes part of the context, while the stove perhaps is form."

The caveat arising from Alexander's comments is that although there must eventually exist a clearly defined product interface that separates detailed information about the product and its context, it may be prudent, during the early stages of building an Information Web, to refrain from hasty placement of this prime interface. The outcome
of the project can be greatly influenced by the placement of the interface, and it may be wise in the early stages to concentrate only on gathering the initial project information with which to begin building the web. The information learned during the early stages could direct the eventual placement of the interface in a much different place than may have been originally expected, before much was known about the project.

With respect to multiple interfaces, in addition to the prime interface, we may quote Alexander yet again;

"A designer is bound, if he knows what he is doing, to be sensitive to the fit at several boundaries within the ensemble at once. The internal coherence of an ensemble depends on a whole net of such adaptations. In a perfectly coherent ensemble we should expect the two halves of every possible division of the ensemble to fit one another.

It is true, then, that since we are ultimately interested in the ensemble as a whole, there is no good reason to divide it up just once. We ought always really to design with a number of nested, overlapped form-context boundaries in mind. Indeed, the form itself relies on its own inner organization and on the internal fitness between the pieces it is made of to control its fit as a whole to the context outside."

In those projects where these further subdivisions are possible and desired, they can be
seen as dividing the Information Web into sub-solutions and sub-problems, much as Cross (1989) has shown in his symmetrical problem-solution model, Figure 20. Sub-divisions may not be necessary in the simplest projects, and multiple hierarchies of nested sub-divisions may be necessary and desirable in much more complex projects. In the Creme-lite mixing tank example, some sub-problems were the food handling machinery requirements, and the mixing, cooling and heating requirements of the food product. Some sub-solutions were the tank body, paddle and bearing material selections, the fluid drag, gearbox and motor power calculations, and the water jacket and its plumbing.

To summarise, the overall collection and organisation of design information, which is mirrored by the building of an Information Web, is an essential activity and the goal of designing, and should be approached with speed and vigour. It is necessary to identify as many potentially important concerns as possible, and to quickly begin to develop and test the relationships or importance of one to another. In contrast, structuring the subdivisions within the Information Web, and in particular the placement of the prime interface division, should be approached with care and caution. The final placement of these divisions, particularly of the prime interface, can dramatically alter the outcome of the design project.
Summary

In this section on Information we have looked at ways in which it can be modeled independently of time, and have presented and described an Information Web model. This model is suggested to have potential utility as a computer-supported design information storage and display tool, and it has demonstrated the modelling of design information as a separate independent dimension or a modelling framework. The structuring of the model into component parts, divided by a prime interface, has also been demonstrated and discussed. In terms of the modelling framework, this structuring of the Information Web model represents divisions in the information results dimension. The prime interface represents the division between the product and its context. The inputs and outputs which will cross this interface represent the product’s behaviour. Other interfaces within the product, or within the context, can similarly define and describe the interactions of various smaller parts of the web, by highlighting the relationships which intersect those additional interfaces. These may be seen as the relationships among sub-problems, among sub-problems and sub-solutions, or among sub-solutions.
5.4 DOMAIN

Having examined the fundamental characteristics of Time and Information, and their use as dimensions in the modelling framework, we now turn our attention to Domain. We have suggested that Domain is a third fundamental characteristic and modelling dimension of designing. In this context Domain is used to specifically refer to the location or medium in which some design information is represented. Some important domains are the internal domain of the mind, the various external physical modelling domains of drawings, models, text or speech, and the domains of actual physical products, artifacts and people.

As seen in the literature review, while the concept of separate cognitive and physical domains is known and accepted, the potential of modelling design activities and information with respect to these domains does not appear to have been widely explored. This may be another result of academic and professional specialisation. In general, it may be said that the technical design disciplines have a dominant focus on understanding the working principles and the characteristics of technical systems, resulting in an almost exclusive focus on technical objects in the external, physical domain. In contrast, it is cognitive psychology which has a dominant focus on the workings of the human mind, and therefore encompasses study of the internal, cognitive domain. Members of either specialisation would likely become knowledgable in various aspects of either domain, but not necessarily in aspects of both. Designing greatly involves mental processes in the
internal, cognitive domain. Because technical designers and theorists are less knowledgable in this area, it is most probable that understanding designing could be improved by paying more attention to the importance of domain, and to the functional characteristics of the internal, cognitive domain, as revealed in the continuing work of cognitive psychologists. It is also probable that it will be the responsibility of technical design academics and theorists to seek out this knowledge, as cognitive psychologists will not necessarily develop and supply a great deal of knowledge that is specifically and directly aimed at the practical and educational needs of engineering designers.

As a useful third dimension in the modelling framework, it is suggested that domain is both independent of time and information results, but is also usefully interrelated to those two dimensions. Both independence and relationship will be discussed with respect to the modelling dimensions of time and information.

**Time and Domain**

It has been observed that modelling in the time dimension of designing is best done by the conventional design process model, which typically features a sequence of design activities. It is now suggested that the location, or domain, of those activities is an independent additional dimension, that can add to the understanding of the design process beyond what is normally provided by the typical activity-sequence model.
A re-examination of design activities with respect to domain leads to the observation that design activities may be classified according to two categories. They are:

1. Design activities which generate new design information within a particular domain. This information is original to the design project.

2. Design activities which operate between domains, to copy or map existing information from one domain to another. The information in question, while already existing in the project in one domain, is newly copied to another domain.

Certain complex design activities may combine both of these simpler categories.

Examples of the first category of original information generating activities are various thinking or computational activities which occur either completely within a designer's mind, or within a computer or calculator. The evaluation, optimisation, analysis, or synthesis of information may also fit in this category.

Examples of the second category of information transference activities are: observation, reading or recognition, all of which describe a transferred copy of information from the physical world to an individual's cognitive world; drawing or recording, which describe a transfer from the mind to the external world; and even printing and plotting, which describe the transfer of information from the electronic domain of a computer system to
the paper and ink domain of printed text or a plotted drawing.

An example of a complex activity that combines both of these simple categories is sketching, which involves the transfer and feedback of information between two domains, a designer's mind and the sketch itself. Unlike a simple transfer of existing information from one domain to another, sketching, which has been described as visual thinking, is an activity which acts to generate new results in both the physical and the cognitive domains, assisted by the transference of information back and forth between the domains.

Information and Domain.

Maintaining the separation of the information and domain dimensions of the modelling framework requires a re-definition of design information results. We want to avoid the difficulty of discussing information about domains and information about information.

Previous discussions of information were only concerned with the content of the information, and whether a particular piece of information was known or not, with respect to the overall design project. It dealt with the design project as if it occurred in a single domain, necessitating only a single copy of any piece of information. The addition of the domain dimension in the modelling framework is a recognition that designing must occur in at least two domains, and the information content of one domain does not automatically match that of another. It is the dimension of domain, which deals with aspects that relate
to the particular discovery or storage location of the information, or the recording medium
or format which has been used.

It may be recalled that in order to classify all design results as information, it was
necessary to strip the information content of a result away from the medium in which it
was expressed. For instance a drawing was seen as information plus paper and ink. To
include the dimension of domain in the modelling framework of designing recaptures
knowledge of the supporting medium and its characteristics, knowledge that was lost in
the classification of all design results as information. This knowledge of the supporting
medium is relevant to the handling of information, and not to the content of the
information which is to be handled. The inclusion of domain as a separate dimension
from information has the practical benefit of differentiating between generating
information content, and information handling. This allows the consideration of
information content-generation, largely independent of domain, and the consideration of
information handling and communication activities, largely independent of content. This
separation can also assist in the teaching and study of separately applicable design skills
and activities. Finally, the inclusion of domain in the modelling framework also adds
emphasis to the importance of information handling knowledge. It is apparent that
knowledge of information content is crucial, but engineering designers can also benefit
from additional knowledge about how their minds function in helping to generate that
information, and skills they can develop to better record, present and communicate that
information.
The Necessary Importance of Time, Information, and Domain

In order to present summarising and strengthening arguments for the inclusion of domain as an important modelling dimension of 'designing', the importance of the first two dimensions will also be reviewed.

Time is a necessary characteristic of designing, and is a dimension of the modelling framework, as no design project may logically or practically be assumed to take place instantaneously. As a design project takes place over a period of time, and as is documented in design process models, it is generally accepted that there may be a variety of different sub-activities during that time. Beyond this point in the argument, there is less acceptance and agreement, as the large number and the variety of existing design process models says something about the difficulty of agreeing on the descriptions of specific sub-activities and their sequence. Despite this eventual difficulty, time is an accepted important parameter in modelling the design process.

The generation of information is another necessary characteristic of designing, and Information is the second dimension of the modelling framework. The resulting production of information is the rationale for undertaking a design project, and any general model of designing should explicitly discuss or implicitly imply the production of information results. The existing traditional boxes-and-arrows design process models focus on design activities, and because of the fundamental differences between design
activities and design results, these models are not well suited to modelling results. We have seen that a model such as the Information Web is better suited to store and display design results.

The Time-Results model bridges the gap between process models and information graphs, and models both activities and results in the dimensions of Time and Information. The model has the potential for design process efficiency measurement.

Domain is a necessary characteristic of designing, and is the third dimension of the modelling framework. Domain is an important characteristic, as no design project can be completed within a single domain. A project cannot be completed entirely within the internal cognitive domain of a designer's mind, and the results of a design project cannot simply appear in some external physical domain. There must be evidence of a project in some external domain, and the results must have been generated in some internal domain. Because of the necessary involvement of at least two domains in a design project, it may be deduced that there must also necessarily exist at least one copied transfer, or mapping, of design results from the internal domain to the external. As this transfer is a necessary design activity, it follows that no model of the design activity should be considered complete or accurate, if the activity of transferring information from the internal cognitive domain to the external physical domain is not explicitly or implicitly allowed or described.
The concept of domain is also always implicitly present in any type of model, following the assumption that the purpose of a model is not to represent itself, but to represent something else. As the model is distinct from what is being modelled, this implies the existence of two distinct but related domains, a modelling domain and a real domain.

The preceding discussion is suggested to help establish the necessity of including the dimension of domain within any complete multi-dimensional model of designing, based on the argument that without it the model would be incomplete. On a practical level it is suggested that the concept of domain is important in describing a large number of fundamental inter-domain design process activities, and is useful to separate the skills and activities needed to generate information content from those skills and activities needed to handle information. Presentation and communication are two typical information handling activities, which can be seen to involve the transferring of information from domain to domain. The dimension of domain is therefore of importance in contributing to an improved modelling framework of designing, and consequently to an improved descriptive understanding of designing.
CHAPTER 6

CONCLUSIONS

Despite the range of differing views on design theory, there is agreement that design theory is immature. The problem undertaken by this thesis was to attempt to more clearly identify and solve the problem(s) of design theory. The identified problem is the lack of an acceptable description of the fundamental characteristics of designing. These fundamental characteristics would be the building blocks of a theory. Their identification and description will improve our ability to develop a better theoretical understanding of designing. A better theoretical understanding of designing can complement our existing higher level of intuitive and practical understanding, and can assist in both the teaching and practice of designing.

Conclusions

1. Three fundamental characteristics of designing were identified. They are Time, Information, and Domain. They were shown in a simple, idealised description of designing. It is concluded that they are valid, as they were shown to be in two actual design cases.

2. A Modelling Framework for designing was described, based on the dimensions of Time, Information and Domain. The modelling framework is useful in illuminating the
inter-relationships of many design models, including many existing design process models, and the Time-Results Model and the Information Web introduced in this thesis.

3. Traditional activity-sequence design process models are models in the dimension of time. There are many process models, with a variety of design sub-activities and sequences. The models are not well-supported by research. The models are all intended as relatively general models, and are not specifically tailored to different types, kinds, or ranges of design problems. It is concluded that the traditional boxes-and-arrows nature of modelling designing in the time dimension, is better suited to the modelling of activities than it is to results, although results are included in some models.

4. The two primary domains of designing, the internal cognitive domain and the external physical domain are both known, but it is concluded that their role in describing designing is more fundamentally important than has been previously described. The concept of domain separates design activities into two classifications. One class of activities is concerned with the largely domain-independent generation of information content, and the other class of activities is concerned with largely content-independent information handling between domains.

5. An Information Web model was described, which models design information in a connected web, or graph. It is a model based on the dimension of information, and is independent of time and domain. It is a collection, storage and display tool for design
information, and is believed to have the capability of displaying any entities and their
to having the capability of displaying any entities and their relationships that are describable by language. It may be structured along both primary and secondary interfaces, which separates design information into product and context, and highlights their inter-relationships. It is concluded that the Information Web has the potential to become a computer-aided tool, which could have particular utility for teams of designers.

6. The Time-Results model was suggested as an improved method of modelling designing, which includes the two dimensions of Time and Information. It is concluded that with the development of suitable information quantity and quality measurement systems, the Time-Results model has the potential of measuring design process efficiency.

7. It is concluded that one major problem of design theory can be more clearly identified as the lack of a strong descriptive understanding of the fundamental characteristics of designing, in comparison to an existing strong intuitive and practical understanding of designing. The identified factors which have contributed to this situation are the very long history of design practice, and learning by doing, in comparison to a short history of design theory. The study and development of broadly general design theory is also believed to be hindered by the fragmentation caused by design specialisation, in academia and professional practice.

8. A definition of designing was developed, in Appendix C, using a described
methodology. Developing a strong definition of designing is an additional means of developing a stronger theoretical understanding of designing, to complement a practical understanding. The developed definition is:

Designing is: Describing a new possibility, which is expected to allow the achievement of a preferred situation.

Future Research

1. Investigate the further development of the Information Web concept into a useful and practical computer-aided design tool.

2. Develop systems of units of measurement for information quantity and quality. Improved measurement systems will allow improved measurement of the efficiency of a design process, as displayed on a Time-Results graph. Although it would help in project planning, it should not be necessary to also need to know the total quantity and quality of information required to describe a product and its context. Process efficiency measurement alone can indicate faster or slower progress toward a distant goal, regardless of the known or unknown remaining distance to the goal.

3. Develop improved versions of existing design process models, through the use of the
Time-Results graph. Each box on a process model may be checked to verify the name and nature of the activity, and to check or verify its relationship to any identified output results and to any required inputs.

**Summary of Contributions**

1. Extensive collections of both design process models and design definitions were assembled.

2. The thesis attempted to more clearly identify a problem with design theory. The theoretical understanding of designing has historically lagged behind the practical understanding of it, resulting in the lack of a simple, strong, descriptive understanding of the fundamental characteristics of designing.

3. Three fundamental characteristics of designing were identified. These are Time, Information, and Domain. These independent, inter-related characteristics allow a simple description of a design project.

4. A three-dimensional modelling framework was developed, based on the identified fundamental characteristics. This framework has connections to traditional engineering design process models, information modelling, and to cognitive psychology.
5. An Information Web model was described, as the concept for a tool to be used to gather, store, and display design project information in a single common location and format. This tool is related to the entity-relationship approach of information database modelling, and sentence modelling in semantics.

6. The Time-Results model was presented as a suggested improved method of modelling the design process in the two dimensions of Time and Information Results. Unlike the boxes-and-arrows activity-sequence design process models, the Time-Results graph models activities and results separately, according to their different natures. With the development of suitable information quantity and quality measurements, the Time-Results model has the potential capability of displaying useful measurements of design process efficiency.

7. A definition of designing was developed, as an additional approach to solving the problem of poor descriptive understanding of designing. The definition was developed using existing definitions as a basic source of issues and concepts. Both the definition and the methodology for achieving it are presented in Appendix C. The definition is:

   **Designing is:** Describing a new possibility, which is expected to allow the achievement of a preferred situation.
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Fig. 48. A composite view of the systems engineering, development and manufacturing process.
Figure 2. Asimow (1962)
Figure 3. Asimow (1962)
Figure 4. Archer (1965)

Figure 5. Archer (1965)
Block diagram of the design process.

Figure 6. Dixon (1966)
Design process flow chart.

Figure 7. Vidosic (1969)

Model of the design activity.

Figure 8. Markus (1970)
Figure 9. French (1971)
Fig. 6. The PDI (production/deduction induction)-model of the rational design process described in the text. The diagram suggests a cyclic, iterative procedure PDIPDIPD... and so on, with constant refinements and redefinitions being made of characteristics, design and suppositions as the composition evolves. In fact the model is envisaged as representing a critical, learning process in that statements inferred at later stages may be used to modify those used in earlier stages and thus to stimulate other paths of exploration. For this reason no arrows are shown along these paths, although the general direction of argument is clockwise.

Figure 10. March (1976)
Formal Iterations in the Design Process.

Figure 11. Love (1980)

Seven Systematic Steps Within a Design Phase.

Figure 12. Love (1980)
The structure of action in general.

Figure 13. Eekels (1982)
Figure 14. Eekels (1982)
Fig. 13 General Procedural Model of the Design Process.
NOTE: referring items 1.2, 1.3, and 1.4 see also note in Table 4, section B, item 1.

Figure 15. Hubka (1982)
Figure 16. Kardos (1983)
Figure 17. Pahl and Beitz (1984)
Figure 18. VDI (1987)
A simple three-stage model of the design process

Figure 19. Cross (1989)

The six stages of the design process positioned within the symmetrical problem-solution model

Figure 20. Cross (1989)
Figure 21. Shigley (1989)

Analysis, synthesis, and evaluation as a recursive process.

Figure 22. Coyne et. al. (1990)
The three design phases of analysis, synthesis, and evaluation.

Figure 23. Coyne et. al. (1990)

\[ \frac{Y}{X} = \frac{G}{1-GH} = \frac{G}{GH} = H^{-1} \text{ for } GH > 1 \]

Feedback control loop depicting the design process. \( Y \) is the desired output, \( X \) is the input, \( G \) is the synthesis capability, and \( H \) is the analytical ability. Large \( GH \) helps the sign process. The ability to judge the quality of the design quickly helps the design process.

Figure 24. Suh (1990)
Figure 25. Pugh (1991)
Figure 26. Eekels and Roozenburg (1991)
Figure 28. Eder (1988)
Figure 29. Hofstadter (1979)
Figure 30. McLuhan and Davies (1966)
Figure 3.5 Cause-and-effect diagram for wobbling (dispersion analysis)
Figure 32. Leech (1974)
Figure 3.2: An information model for a news archive

Figure 33. Veryard (1992)
Figure 3.3
Global ER schema and functional areas.

Figure 34. Teory (1990)
Figure 2.3
Comparison of ER construct conventions.
Figure 5 - Barrier to Visual Thinking in the Design Process

Figure 36. Radcliffe and Lee (1990)
Figure 37. A Modelling Framework for Designing
Figure 38. Activity-Sequence Base Unit

Figure 39. Activity-Sequence Model w/ Feedback Loops
Figure 40. One-Dimensional Model of an Activity

Figure 41. Two-Dimensional Model of an Activity

Figure 42. Model of an Activity and its Results
Figure 43. Time-Results Graph
Figure 44. Activity Input-Output Model

Figure 45. Deduction Input-Output Model
Figure 46. An Innovative Activity

Figure 47. An Input-Dependant Activity
Figure 48. 3 Possible, Multiple-Activity, Time-Results Models

a) fully innovative, independent

b) input-dependent, fully embedded

c) partially dependent, partially embedded
Figure 49. Information Web - Creme-Lite Mixer
Figure 50.
Information Web
Definitions of Designing
Appendix A

Creme-Lite Mixing Tank Case Study
Design of a Creme-Lite Mixer

This case is intended to show the student the full spectrum of design engineering activity from requirement definition to trouble-shooting in the field. Of special interest is the fact that the case demonstrates the use of several engineering sciences in an elementary way. The division of the case into three parts permits the assignment of projects, the results of which can be later compared with the results in the case.

The exhibits in the case demonstrate how the practicing engineer uses the various engineering subjects in making technical decisions.

Exhibit B-1 Pressure Vessel Design
Exhibit B-1 Fluid Dynamic Drag
Exhibit B-3 Elementary Calculus
Exhibit B-5 Torsional Stressing
Exhibit B-5 Motor, Chain, Bearing Selection
Exhibit C-1 Heat Transfer

Part A

This segment of the case deals with problem definition. Class discussion can be centered around:

- Food handling equipment special requirements
- Vagueness of performance requirements
- Why viscosity of creme-lite is required
- George's method of getting the 'feel' of the creme-lite
- Determination of power requirements
- Mixer paddle sizing and arrangement
- Tank design for 10 psi
In addition to the above, the student can be assigned the task of determining the power requirements of the mixer and sketching a paddle arrangement. It should be impressed upon the student that the paddle arrangement selection should be made on a rational basis, not just appearance.

Part B

This segment, with its exhibits, demonstrates the solution to the requirements that George arrived at. Close scrutiny of the exhibits will reveal his rationale for the decisions that resulted in the final design. Besides comparing the assignment against George's solution, class discussion can be centered around:

- The relative merits of the two drag calculations made; one using average velocity, the other integrating over paddle faces.

- Significance of Reynolds number.

- The reasons for selecting paddle sizes to produce zero shear on the central shaft.

- Tank wall thickness was determined both from elementary strength of materials and ASME code; what are the merits of each and how was the final design established.

- The motor selection.

- The selection of V belt and chain drives.

- How to calculate the time it will take to cool a tank of creme-lite from 130°F to 80°F.

Parts A and B may be used as an assignment in graphics. Based upon the design details given, the student could be asked to make layouts or finished drawings of the mixer tank.

Part C

This segment of the case contains the finished drawing of the tank and the mixer and the heat transfer calculations. The body of the case outlines the subsequent field service problems. The class discussions could be centered around:
- Merits of the design.
- What caused the gear box failure.
- George's handling of the problem.
- Should the unit have been originally supplied with 3 hp. motors.

Assignments could be made in graphics to make drawings of some missing mixer details.
Design of a Creme-Lite Mixer (A)

The telephone rang; it was Charlie Menzie.

"George, would you go down to West's, please," he said, "they are having trouble with the creme-lite mixer that you designed."

Charlie could give no further information about the trouble. Webb, the Plant Engineer at West Ltd., had telephoned Charlie to have someone come down to see about fixing the mixer which had broken down shortly after it had been put into service. Charlie asked George to see what the trouble was and to find out what had to be done to fix it.
George Crassa was a professional engineer with 15 years of industrial experience. He had recently joined Roche Inc.; the Creme-lite mixer for G. West Ltd. was his first project for the company. Roche Inc. was a small steel fabricator specializing in tanks and other light gauge steel weldments. Until George joined them, Roche Inc. did not have an engineer on staff. Their expanding business and demands for original equipment by their customers had required them to increase their technical staff. A year before they had hired Harry Anson, a senior draftsman. George and Harry now comprised the entire engineering staff.

Before joining Roche Inc., George had worked in a variety of industries from a heavy machinery manufacturer to a firm making aircraft instruments. This varied background had convinced him that original design was based upon a knowledge of the fundamentals. The differences between the technologies of the different industries he had worked in were only a matter of emphasis. It was George's habit, when faced with an unfamiliar problem, to fall back on fundamentals and build his knowledge from there.

Charlie Menzie was a salesman with Roche Inc. and a personal friend of Georges. In fact, Charlie had been instrumental in recruiting George to join Roche Inc. Charlie hadn't any formal technical training but was one of those quick bright people who grasped things quickly and who was a bundle of energy.

As George drove down to West's plant, he turned the project over in his mind to see if he could anticipate what had happened.

Charlie had made contacts at G. West Ltd. They had wanted a special tank built for handling creme-lite. Roche Inc. wanted the job badly for two reasons: first it would be an introduction into a new area, and secondly, the shop was running short of work. Because of the nature of creme-lite, considerable engineering would be required in this case.
G. West Ltd. was a large commercial baker which had several plants across the country. The Montreal plant not only supplied bread, but also made a large variety of packaged cookies and cakes. They proposed to use a newly developed edible fat, creme-lite, for their icings and fillings. The proposed tank mixer was to store and process the fat.

Creme-lite is produced by Canada Packers Ltd. It had some peculiar properties, which made it especially suitable for icings; but these properties also made it somewhat difficult to handle. The fat is delivered in tank car lots at a temperature between 80° and 130°F. In this state it is a clear golden liquid. If the temperature is raised above 130°F, it burns and turns brown making it unacceptable for baking. If cooled below 80°F, it has two states. If cooled while being agitated or stirred, it forms a smooth, free-flowing, white cream-like substance, much like butter, (hence its name). If it is allowed to cool without stirring, it crystallizes and forms a hard granular fat. In the latter state it is completely unsatisfactory for inclusion into the icings or for handling.

The purpose of the mixer was to receive and store approximately 600 gallons of creme-lite at approximately 130°F. The tank was to be double jacketed so the cooling water could be used to cool the creme-lite to just under 80°F overnight. During the cooling, the creme-lite was to be continually agitated to prevent it from crystallizing. Once at the lower temperature, steam would be introduced into the jacket to mix with the water to hold it at approximately 80°F. During the day, the creme-lite was to be drawn from the bottom of the tank into the process.

Since the creme-lite was for human consumption, the tank design had to meet food handling machinery requirements. Parts in contact with the fat were to be of stainless steel. The design must be such as to prevent contaminants getting into the fat. Reentrant cavities in the fat were to be avoided to prevent accumulation of fat which would go rancid. Although the tank was to be flushed with steam between fills, reentrant corners could still cause trouble.
Charlie and Webb had made sketches of the proposed tank to determine sizes. The tank was to be approximately 5 feet, inside diameter, 5 feet high with a conical bottom. The top of the tank was to be 10 feet off the ground. The tank would be supported by 3 legs. Lids were to be provided for the top with a catwalk so that inspection and flushing with a steam hose could be carried out.

Before proceeding further with the design, Charlie and George went to see Webb at G. West Ltd. in order to establish the exact requirements of the mixer. This was most important since they were putting in a bid which was minimal, therefore Roche Inc. could not afford to have any misunderstanding as to requirements. Because Roche needed the job, the estimates had to be correct, there was no margin for error. Any additions that had to be carried out that had not been allowed for in the estimate could be the difference between a profit or loss on the job. Several hours were spent with Webb discussing detailed requirements. These were then presented to Webb in writing, which he approved (Exhibit A-1).

Of special note is item 9. Webb could not clearly establish the required mixing rate, therefore, he requested that provisions be made for changing the speed of the mixing paddles from 12 rpm to 20 rpm by some simple means such as changing belt sheaves.

Scrapers were required at the walls because it was felt that crystallization would start on the walls and if this material was not turned back into the mix it would form an insulating barrier between the cooling water and the hot fat.

It was later requested that the inner tank be designed to carry 10 psi working pressure. Webb felt that at some future date they might wish to convert the tank to a pressure vessel. For this purpose, the inner tank was to be designed to meet the ASME code for Unfired Pressure Vessels.

Webb also wanted to know the time it would take to cool the creme-lite from 130°F to 83°F. He wanted to be sure he could cool it over-night.
Before proceeding with the design, George decided to find out more about the creme-lite, since its properties were essential to the design. He and Charlie went to Canada Packers and spoke to several people about creme-lite. Canada Packers were of little help. They offered to provide all the creme-lite needed for testing, but outside of stating that its density was between .93 and .94 and that crystallization takes place at 83°F, they knew little about its physical properties. They had no viscosity figures. Nor could they explain the mechanism of crystallization or specify the mixing speeds needed to prevent crystallization.

Charlie took a sample of creme-lite to another of his customers, one in the adhesive business, to measure the viscosity of the creme-lite. George took a sample home to get the "feel" of it at various temperatures and to try to establish some mixing parameters.

Measurements established the viscosity of the creme-lite under continuous mixing at 80°F as 350 centipoise. This figure was used in all subsequent calculations. This is about the same as S.A.E. 30 oil at 68°F.

George, on his part, took a 10 lb. sample of creme-lite home and on his stove did some heating and cooling tests, measuring the temperature of the fat with a laboratory thermometer. The first time he cooled the fat without mixing. The result was an extremely granular product as soon as the temperature dropped below 80°F; quite comparable to lard taken out of the refrigerator. After heating it again, he allowed it to cool while stirring gently. The fat stiffened while cooling, but it was not difficult to stir. With stirring, he found it was possible to keep it smooth and creamy well below 80°F. Seconds after he stopped the mixing, the creme-lite crystallized and became hard. On re-heating, he noted that the creme-lite melted very quickly around the edges of the pot, but did not readily melt in the center. It was necessary to cut the solid core into pieces to increase the melting rate.
With this background, George started to design. First a schematic was made (Exhibit A-2). The tank proportions were established from the requirements. The outer jacket was to be 2 inches from the inner to allow for cooling water. Steam was to be introduced at the bottom.

An electric motor was selected to drive a worm gear reducer through a V belt. Wherever possible, Roche Inc. used "Croft" worm gear reducers (Exhibit A-3). The reducer was to drive the mixing shaft by means of a chain belt operating in a horizontal plane.

The bottom bearing of the mixer shaft had to be located in the creme-lite; this bearing would be of nylon. The scrapers for the wall were also to be of nylon.

The schematic layout is shown in Exhibit A-2. The selection of the gear reducer and motor would be dependent on the power consumed by the mixing. This in turn would be dependent on the mixing paddle design.
1. Tank to be basically in accordance with Roche quotation 123-64 sketch date 8 June.

2. Cover to have two hinged lids.

3. Inner tank to be of 304 stainless steel. Mill finish with welds ground "smooth".

4. Tank will have a working capacity of not less than 600 imp. gallons.

5. Outer shell to be of carbon sheet.

6. Platform to be provided at access ladder to permit operator to flush tank.

7. Food handling cleanliness requirements to be met, no corroding material to be in contact with product, contaminants must be prevented from entering processed product, no recesses or voids that may trap product are to permitted.

8. Two inch radial spacing between inner and outer jacket required for circulation of water and steam.

9. Raddles to be driven at nominally 15 rpm. to be provided, paddle speed to be variable from 12 to 20 rpm by change of drive sheaves.

10. Scrapers to operate against inside wall to prevent accumulation of product on the wall.

11. Connections will be of the following kind:

   1. Product inlet: 2" Male P. & C.
   11. Product outlet: 3" Male 10 304ss
   11. Steam inlet: 1" Male C. & C.
   IV. Water inlet: 1" Male C. & C.
   V. Steam and water drain: 2"
   VI. Water drain.

12. Product will be Canada Packers "Creme-Lite".

APPROVED: [Signature]
[Date]
EXHIBIT A-2  SCHEMATIC DRAWING OF MIXING TANK
Selecting a Worm Gear Reducer

When selecting a "RADIATION" Worm Gear Reducer it is necessary to determine the following factors:

1. The maximum horsepower or torque required to drive the driven machine.
2. The speed in R.P.M. at which the driven machine is to run.
3. The starting-up load (this must not be underestimated).
4. Shock loads.
5. Any overload which may be imposed on the Worm Gear Reducer.
6. Speed in R.P.M. of the motor or the prime mover to be used.

In determining the maximum horsepower required to drive a particular machine, the operating characteristics must be taken into account. To assist in determining the appropriate Service Factor, load and duration classifications against service factors for a variety of machinery drives are given below.

Horsepower for unit selection is obtained by multiplying the normal horsepower by the service factor for the particular type of duty for which the gear reducer is required. The resultant figure should be used to select the size of gear reducer required from the Rating Tables.

The Rating Tables tabulated on pages 4 to 8 are based on 12 hours' continuous running with temperature rise of not more than 100°F and provide the following information for each size of reducer: Nominal ratio, Exact ratio, Input shaft speed, Output shaft speed, Input H.P., Output H.P., Output torque in lbs./in.

The Thermal Rating is based on a maximum oil temperature rise of 100°F above ambient with a maximum permissible oil temperature of 200°F.

For all input speeds of less than 100 r.p.m., it is advantageous to use Output Torque Ratings (lbs./in.) listed, in preference to horsepower. Since, at these low speeds, static conditions are approximated, it is not necessary to apply Service Factors.

In determining the size of reducer to accommodate shock loads, refer to the table below which gives Load Classification and duration of running time with Service Factors to be used when driving specified classes of machinery.

The permissible overhung load values, applicable at the centre of the output shaft extension, are tabulated on pages 10 and 11.

HINTS FOR SELECTING A GEAR REDUCER

STAGE 1: Decide the type of "RADIATION" Worm Gear Reducer most suitable for the proposed drive.

STAGE 2: The required ratio can be obtained by dividing the input speed R.P.M. by the R.P.M. of the driven machine (assuming the worm gear is to be coupled direct to the driven machine).

STAGE 3: Determine the input horsepower or output torque necessary for the drive, taking into account the relevant factor for the proposed duty as outlined above.

STAGE 4: Reducer size can now be determined, having decided the ratio, input speed and capacity. Refer to Output Rating Tables tabulated under input speeds ranging from 10-1800 r.p.m. and select a unit with equal or higher rating from the appropriate table.

STAGE 5: If a V-sheave, Pinion, Sprocket, etc., is to be mounted on the output shaft, check overhung load, or if vertical drive, thrust load. Permissible loads are tabulated on pages 10 and 11.

STAGE 6: Size and type of reducer now established, refer to appropriate page providing relative dimensions and shaft assemblies.

SERVICE FACTORS

<table>
<thead>
<tr>
<th>CLASS OF LOAD AND DURATION OF RUNNING TIME</th>
<th>Electric Motor</th>
<th>Gas Engine Multi-Cylinder</th>
<th>Gas Engine Single Cylinder</th>
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</thead>
<tbody>
<tr>
<td><strong>UNIFORM LOAD</strong></td>
<td>Hours per day</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>Agitation and Mixers, liquid, semi-liquid; Conveyors, Elevators, (Bucket), Food Industry, Bottling machines, etc. Pumps, gear, rotary; Screeners, Ait washing, traveling water.</td>
<td>.. ..</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>.. ..</td>
<td>24</td>
<td>125</td>
<td>15</td>
</tr>
<tr>
<td><strong>MODERATE SHOCK LOAD</strong></td>
<td>Hours per day</td>
<td>3</td>
<td>125</td>
</tr>
<tr>
<td>Agitation and Mixers, variable density, Conveyors, not uniform load; Bucket Elevators, Food Industry, slicers, mixers, grinders; Laundry Tumblers, Laundry; Pumps (reciprocating), Screens (rotary, stone, gravel). Textile machinery (batchers, calendars, mangles, openers, spinners, loom frames).</td>
<td>.. ..</td>
<td>125</td>
<td>125</td>
</tr>
<tr>
<td>.. ..</td>
<td>24</td>
<td>125</td>
<td>15</td>
</tr>
<tr>
<td><strong>HEAVY SHOCK LOAD</strong></td>
<td>Hours per day</td>
<td>3</td>
<td>175</td>
</tr>
<tr>
<td>Brick &amp; Clay machinery (presses, briquette machines), Conveyors (reciprocating, shaker), Metal Mills (drawbench, slitter, wire drawing),</td>
<td>.. ..</td>
<td>175</td>
<td>175</td>
</tr>
<tr>
<td>Pumps (reciprocating).</td>
<td>.. ..</td>
<td>24</td>
<td>20</td>
</tr>
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For intermittent Service refer to Crafts for selection.
<table>
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<tr>
<th>Nominal Ratio</th>
<th>Exact Ratio</th>
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</thead>
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<td>Input H.P.</td>
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<td>6/1</td>
<td>48/1</td>
</tr>
<tr>
<td>7/1</td>
<td>74/1</td>
</tr>
<tr>
<td>10/1</td>
<td>103/1</td>
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<tr>
<td>12/1</td>
<td>123/1</td>
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<tr>
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<tr>
<td>70/1</td>
<td>700/1</td>
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</table>

<table>
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<th>INPUT</th>
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<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>OUTPUT Torque (lb. in.)</td>
<td>2000</td>
<td>4000</td>
<td>6000</td>
<td>8000</td>
<td>10000</td>
<td>12000</td>
<td>14000</td>
<td>16000</td>
<td>18000</td>
<td>20000</td>
</tr>
</tbody>
</table>

*Note: The values in the table represent engine performance data for a specific engine model. The input and output torques are given in pounds-inches (lb. in.), and the R.P.M. values are in revolutions per minute (R.P.M.). The exact ratio and nominal ratio columns provide specific values for various engine configurations.*
**DIMENSIONS**

**VERTICAL TYPE**

'RV' TYPE
FAN COOLED

For machining limits for shaft extensions, Coupling and Pinion bores refer to page 1.

**DIMENSIONS IN INCHES**

| S | A | B | C | D | E | F | G | H | J1 | J2 | K | L | N1 | P | Q | R | S | T | U | V | V1 | W | X | Y | Z | W1 |
| 40 | 4 | 9 | 6 | 5 | 3 | 1 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 |
| 50 | 4 | 9 | 6 | 5 | 3 | 1 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 |
| 60 | 6 | 11 | 10 | 9 | 7 | 5 | 4 | 3 | 1 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 |
| 70 | 7 | 12 | 11 | 10 | 9 | 8 | 6 | 5 | 4 | 3 | 1 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 |
| 80 | 8 | 13 | 12 | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 1 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 | 1/2 |

**REDUCER ASSEMBLY ARRANGEMENTS**

Output Shaft Extension—Standard Assembly No. 1
—Output Shaft projects in an upward direction and is placed on Right-hand side when looking at the Input Shaft End.

NOTE—Output Shaft can be arranged upwards or downwards, or both. If other than Standard Arrangement is required, please state Arrangement (No. 2, 3, 4, 5, 6 or 7) on enquiry and order.
Design of a Creme-Lite Mixer (B)

George first checked to see that 600 gallons of creme-lite would fit into the tank. (His calculations for the tank design are in Exhibit B-1.) The tank dimensions, 5 ft. diameter, ft. high, with 2 ft. high cone at the bottom was found to be satisfactory. In fact, this left a comfortable freeboard of 9 inches at the top.

Since the tank had to be capable of carrying 10 psi pressure, wall thickness was determined from thin cylinder theory. Nominal design indicated 1/8 inch sheet stainless would be satisfactory. Re-checking against ASME code increased the wall thickness to 3/16 inches. The ribs in the conical portion were designed to carry the total weight of the fat in the tank.

These calculations established the structural requirements of the tank. The power requirements would depend on the paddle design and the resultant drag on the paddles. As a starting point, a paddle arrangement was selected arbitrarily (Exhibit B-2). The arrangement was considered a maximum required. The paddles were arranged to insure that the entire volume was swept. Sketches were also made of the wall scraper arrangement. This paddle arrangement was used in the subsequent analysis. From elementary fluid dynamics, it was known that the drag $D$ was

$$D = \frac{C_D A p V^2}{2}$$

where

- $C_D$ = drag coefficient
- $A$ = projected area
- $p$ = fluid density
- $V$ = fluid velocity

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The drag coefficient is dependent on Reynolds number $R$. Assuming the velocity of the paddle would be the velocity at a mean diameter, 4 ft., the Reynolds number was found to be 1,000. The paddle sections were to be curved plates. The drag coefficient for an infinite flat plate or an infinite circular cylinder at $R = 1,000$ would be 2 and 1.5 respectively.

Therefore, the total drag on a 1 ft. by 6 ft. paddle was determined. The resultant power required at 20 rpm was found to be 1.5 Hp.

If the same paddle is at 2 ft. mean radius, the power required is reduced to .18 Hp.

This difference immediately emphasized the fact that the power requirements and the drag force were extremely dependent on the paddle location. It also indicated that using average velocities for the drag was not too accurate.

A general equation expressing the power requirements for the paddles was derived

$$Hp = \frac{C_D \cdot \rho \cdot A}{66,000} \left(\frac{n}{60}\right)^3 \times d^3 \times n^3$$

For the creme lite, this equation reduced to

$$Hp = 0.255 \times A \times \left(\frac{d^3}{4}\right) \left(\frac{n^3}{20}\right)$$

This equation also showed that power requirements dropped off very rapidly as the speed was reduced from the maximum of 20 rpm.

This formula was used to estimate the power needed and to select the drive units. Since the mixer could be run at 20 rpm, the selections were made for this rating. The scrapers were assumed to have the same drag as the paddles, but acting at 5 feet.
The preliminary calculations indicated a requirement of 1.633 Hp. Allowing for extra drag on paddle arms and any center paddles the total requirement should be less than 2 Hp. It was decided to motorize at 3 Hp. since losses in the gear box and chain drive were expected.

Although the details of the paddles had not been established, the above power calculations were sufficient for selecting the drive motor and the gear box. It was essential to specify those early in the design because they were long delivery items and had to be ordered immediately. From the Crofts catalog the "RV" type fan-cooled reducer size 50 with a nominal ratio of 60/1 was chosen. This has a 2.6 Hp. output at 20 rpm with a 3.8 Hp. input at 1200 rpm.

George called the motor supplier to see if a 4 Hp. 1200 rpm motor was available. They could supply one if necessary, but it would be special; the standard NEMA ratings were 3 Hp. and 5 Hp. Since the standard motor was cheaper, it was decided to use a 5 Hp. 1200 rpm 60 cycle three phase motor.

The drive between the motor and the gear box was selected as a V-belt with 1 to 1 pulleys at 20 rpm. The unit would be supplied with 3 to 4 pulleys initially, for a 15 rpm mixing speed.

Having ordered the drive components, George turned his attention to the detail paddle design. The problem was now to design the most efficient paddle arrangement within the power limitations of the drive component. The previous derivation established the nature of the drag forces and indicated that the arrangement of paddles in Exhibit B-2, although apparently symmetrical on paper, actually was not dynamically symmetric.

George recalled, "I tried several paddle arrangements on a sketch pad. I had made a brief literature search to see if I could get any guidance but I could find nothing. In these various trials, the controlling design philosophy began to
form in my mind. The best design would be one with balanced loading. The dynamic forces on the paddles should be balanced to virtually eliminate the bearing loads." To this end George decided to make the design such that:

1. the paddle should not produce radial thrust,
2. the force on the right and left hand paddles should be equal,
3. the total force on the top set of paddles and bottom set of paddles should be equal.

The first requirement was met by having the paddles slightly bowed, but symmetrical about the direction of motion.

The second requirement could be satisfied by symmetrical construction, but this would have resulted in either large drag with too many paddles or channeling at the paddle radius. Instead it was decided to use two different sizes of paddles at different radii sweeping the entire volume.

The third requirement could be met by having identical paddle arrangements top and bottom except displaced 180°.

It had been previously established that the drag force was dependent on the radius. To establish the size of the paddles to meet the second requirement, a more careful analysis of drag forces was required. It was assumed that the drag on an element of the paddle was dependent only on the velocity. An analysis was carried to determine the relative width of the paddles to have equal drag, (Ex. B-3).

It was found that the drag force was equal to:

\[ F = C \left( \xi_0^2 - \xi_1^2 \right) \]

- \( F \) = drag force
- \( C \) = lumped constants
- \( \xi_0 \) = outside radius of paddle
- \( \xi_1 \) = inside radius of paddle

After some juggling of dimensions, it was decided to use three sets of paddles.
A small paddle, 4 inches wide, 1-1/2 feet high with its outer edge 2 feet from the center; a larger paddle, 6 inches wide by 2 feet high with outer edge at 1 ft. 6-3/8 inches from the center. In addition, perforated full length panels 6 inches wide would be attached on both sides of the center shaft at right angles to the main paddle assembly. (This paddle arrangement is shown in Exhibit B-4).

The power requirements for these paddles were checked and found satisfactory. The size of the torque tube was then determined. (Exhibit B-5)

The remaining details were cleaned up by selecting a Renold single strand chain ASA size 80 with appropriate sprockets. A flange type cartridge bearing was selected for the top bearing and a nylon machined sleeve bearing was used as bottom bearing.

The design was essentially completed. George turned the design over to Harry Anson. Harry undertook the detail design. George explained the requirements and gave him two sketches: the general layout, showing the details of the bearing dirt seal and details of the shaft torque tube attachment; and the paddle arrangement drawing with the method of attaching the scrapers (Exhibit B-4).

With these and the dimension drawings of purchased hardware (Exhibit B-6), Harry proceeded with a layout. When the layout was completed, George checked the design; little change was required. From the layout, Harry proceeded with detailing.

Before the detailing was completed, Webb from West's Ltd. asked that two thermometer wells be added -- one in the water and one in the creme-lite. The required wells were approximately 18 inches long and 1-1/8 inch iron pipe size, lawler separate thermo wells to take type "S" bulb.
Volume: 400 lmr Crawford = 3790 cu ft of Cream-Cilo
= 400 x 0.1605 = 96.2 cu ft

Inside Dim: 5' x 5' (height) +
Shell Ht.: 5'
Cone Ht.: 2'

Volume of Tank: \( \frac{5^2 \times \pi (5 + 2)}{3} \)
= \( \frac{\pi}{6} \times 5 \times 5.666 \) = 111 cu ft

Free Board: \( \frac{111 - 96.2}{4 \times 0.25} \) = 17.56 in x 0.75 ft x 9''

Static Pressure = 8 (60 + 24) x 62.4 = 3.787 x 10^4
= 8 x 62.4 x 3.787 x 10^4
= 32 psi

Additional Operating Pressure = 10 psi
Minimum Allowable Working Press.: 15 psi
Design Pressure = 15 x 2 = 30 psi

\[ S = \frac{P \times d}{2} \]

\[ t = \frac{P \times d}{25} \]

Height = 304 Stainless Stee
Yield Strength = 30,000 psi
ASME Design Stress = 12 psi
Assume Joint Eff = 100%

\[ c = \frac{30 \times 60}{2 \times 1400} = 0.0805'' \]

100 psi sheet joint eff = \( \frac{0.0805}{2.5} \) = 60%

\[ \delta_0 = \frac{30 \times 60}{.25} = 7200 \text{psi} \]
ASME Code: For Class 3 vessels
Single-welded Butt joints Less than 1/4 in thick
Use Design Stress 5000 psi.

\[ \frac{C_2}{2} \times 5000 \div 900 = 0.16 \text{ min.} \]
\[ \frac{C_2}{2} \div 5200 \]
\[ S_0 = 0.1875 \text{ in.} \]

Ribs on Tank Cone

No. of ribs = 9
Load per rib = \( \frac{5400}{9} \)

If only 3 legs, load per leg = \( \frac{5400}{3} \) = 1800 kg

\[ S = \frac{6M^2}{EI} = \frac{6 \times (2)^2}{6 	imes 6 	imes 3} = \frac{24}{108} = \frac{1}{4.5} = 0.333 \]

\[ S \times \frac{M}{E} = \frac{600 \times 1800}{3.33} = 18000 \text{ Concentrated load} \]

\[ S = \frac{M}{E} = \frac{600 \times 30}{2} = \frac{9000}{2} = 4500 \text{ in lb} \]

\[ S = \frac{9000}{600 \times 30} = 27000 \text{ psi. Uniformly loaded} \]

Uniformly spread load

\[ R_1 = \frac{10000}{3} \div 600 \times 30 = \frac{6000}{18} \]

\[ R_2 = 18000 \text{ psi} \]

\[ S < 18000 \text{ psi} \]
Drag: $D = \frac{C \cdot A \cdot p \cdot V^2}{2}$

- $A$: Projected Area
- $p$: fluid density
- $V$: velocity
- $C$: drag coefficient

\[ \mu = \text{viscosity (cP) \times \text{area} \times \text{speed} \times \text{density} \times \text{length}} \]
\[ \mu = 350 \times 0.000072 \quad \text{avg. sec} \quad \mu' = 0.0073 \]

$R$: Reynolds Number $= \frac{\rho \cdot V \cdot L}{\mu}$

\[ \rho = \frac{5 \text{slug/s}}{\text{ft}^3} \quad V = \frac{\text{ft}}{\text{sec}} \quad L = \text{ft} \]

\[ \mu = \frac{5 \text{slug/s} \times \text{ft} \times \text{ft}}{\text{ft} \times \text{sec}} = \frac{5 \text{slug/s}}{\text{ft} \cdot \text{sec}} \]

\[ R = \frac{62.5 \times 9}{0.0073} = 1.75 \quad \text{slug/s/ft}^2 \]

$C = \frac{L}{\text{ft}}$

$\frac{h}{v} = \frac{2 \times 0.5 \times 20}{3} = \frac{2 \times 0.5 \times 4.2}{1.5}$

\[ R = \frac{1.75 \times 4.2 \times 1}{0.0073} = 1000 : 10^3 \]

$C_d = 2$: infinite flat plate at any angle
$C_d = 1.5$: infinite circular cylinder 1° dia.
Assume Paddle 1' x 6' Area A = 6 ft²

\[ D = \frac{26 \times 6 \times 1.25 \times (4.2)^2}{2} \]

\[ D = 1.18 \times 6 \times 125 = 183 \text{ lb} \text{ - SAY 200 lb} \]

Torque : \[ 200 \times 2 = 400 \text{ ft-lb} \]

@ 20 rpm

\[ \text{HP} = \frac{200 \times 2 \times 2 \times 20}{33,000} = \frac{16 \times 4}{33} \text{ = 1.91 HP} \]

Assume 80% Eff. of Drive \text{ - 1.91 HP.}

1st All of Paddle 1' x 6' 1 ft

\[ V = \frac{W \times 2 \times 60}{3} = \frac{1 \times 2}{3} = 2.1 \text{ ft/sec} \]

\[ D = \frac{2 \times 1 \times 1.25 \times (2.1)^2}{2} = 45 \text{ lb} \]

Torque : \[ 45 \times 1 = 45 \text{ ft-lb} \]

\[ \text{HP} = \frac{45 \times 7 \times 2 \times 20}{33,000} = 0.18 \text{ HP} \]
\[ D = \frac{C_D A \rho V^2}{2} \]

\[ N_p = \frac{D \times V}{33,000} = \frac{C_D A \rho V^3}{2 \times 33,000} \]

\[ V = \frac{N_p \times D}{60} \]

\[ N_p = D \times \frac{C_D A}{2 \times 33,000} \times \left( \frac{D \times d \times n_m}{60} \right)^3 \]

\[ N_p = \frac{C_D A}{2 \times 33,000} \times \left( \frac{D^3}{60} \right) \times d^3 \times n_m^3 \]

where \( C_D = 2 \) and \( \rho = \text{density (slug/ft}^3) \)

\[ N_p = 0.255 \times A \times \left( \frac{d}{7} \right)^3 \times \left( \frac{n_m}{60} \right)^3 \]
$D = 4'$

$D \cdot \frac{1}{2} = \frac{D^2}{2} = \frac{4^2}{2} = \frac{16}{2} = 8$

$A = 2 \times 2 \times 125 = 7$

$NP = 0.255 \times 7 \times \left( \frac{\frac{2.5}{2}}{\frac{2.5}{2}} \right) \times 0.20$ (20 rpm)

$= 0.255 \times 7 \times (0.88)^3$

$= 0.255 \times 7 \times 0.242$

$NP_{cups} = 0.733$ N.P. (cups)

$NP_{cups} = 0.733$ N.P. (cups)

$D = 5'$

$A = \pi \cdot 5 \cdot 5 = 25 \pi$

$NP_{cups} = 0.255 \times \frac{25}{5} \times \left( \frac{2.5}{2} \right)^3$

$NP_{cups} = 1.2$

Total in hay tank: 0.733 + 1.2 = 1.933 N.P.

For 2 N.P. for total tank

Torricelli No 3 N.P.
To make drag on inner and outer mixing both increase

\[ F = C_d A V^2 \]
\[ V = \pi d \times \text{rpm} \]
\[ F = C_d \frac{\pi d^2}{3} (\text{rpm})^2 \]

\[ F = \frac{K'A d^2}{3} \]
\[ d \ell = K'h \ell^2 d \ell \]
\[ F = K'h \int_0^l \ell^2 d \ell \]
\[ = \frac{K'h}{3} [\ell^3]_0^l \]
\[ = \frac{K'h}{3} [l^3 - 0^3] = C (l^3 - 0^3) \]

In total plate \( l_1 = y \)
\( l_2 = 1 \)
\( l_3 = \frac{63}{y} \)
\( l_4 = 6 \)

\( (l_3^2 - l_1^3) = 63 \)

Inserts each will \( \frac{63}{y} = \frac{l_3}{l_1} \)
\( \ell_2 - \ell_1 = \frac{63}{y} = l_3^2 - 1 \)
\[ L^3: \frac{62}{4} = 15.75 \]
\[ L_2 = \sqrt{16.75} = 4.08 \]
\[ (L^3 - L_2^2) = \frac{62}{4} \]
\[ L_3^3 - 16.75 = \sqrt{\frac{62}{4}} \]
\[ L_3^3 = \frac{62}{4} + 16.75 = \frac{62}{2} \]
\[ L_4 = 1.5 \]
\[ L_4^2 - L_3^2 = 64 - 53.8 \]
\[ L_2 = 4 \quad L_3 = 2 \]
\[ L = c (64 - 8) = 56 \]
\[ \frac{L}{2} = \frac{56}{2} \]
\[ \frac{L}{2} = h \frac{56}{2} = h (L^3 - L_2^3) \]
\[ \frac{52}{2} + 8 = L_3^3 \]
\[ \sqrt{52} \]
\[ L^2 - L_3^2 = 3 \]

\[ (L^3 - L_2^3) = \frac{56}{2} = \frac{15}{2} \]
EXHIBIT B-3 (Cont.)

\[
L_2^3 = 21 + 8
\]

\[
L_2 = \sqrt[3]{29}
\]
EXHIBIT B-5  DETERMINATION OF TORQUE TUBE SIZE

\[ FR = 0.25 \times A \times \left( \frac{d}{4} \right)^2 \left( \frac{\text{in}}{20} \right) \]

Screwons
\[ A = \frac{d^2}{4} \times 5 \times 2 = 2.5 \, \text{ft}^2 \]
\[ d = 5 \, \text{ft} \quad \frac{d}{4} = 1.25 \]
\[ \left( \frac{d}{4} \right)^3 = 1.25^3 = 1.958 \]

\[ HP = 1.25 \times 1.98 \times 0.255 = 0.63 \, \text{HP} \]

Outerex Paddle

\[ HP = \frac{255^2}{\sqrt{3}} \times A \left( \frac{d^3}{V} \right) \]
\[ \frac{255}{5} \times A \, d^3 = \frac{255}{64} \times 1 \, d^3 \]

\[ = 0.0399 \times 1 \, d^3 \quad \text{(HP)} \]

\[ HP = 0.0399 \times k \, d^2 \, dx \]

\[ d/HP = 0.0399 \times k \, L^2 \, dx \]

\[ HP = 0.0399 \times k \int L^2 \, dx : 0.0399 \times k \int 1^2 \, dx \]
\[
\text{HP: } \frac{0.00399 h}{4} (l'' - l')
\]

Set \( h = 1.7 ft \)

\[
\text{HP: } \frac{0.00399 \times 1.7}{4} (l'' - l')
\]

\( l'' = 4 \quad l' = 256 \)

\[
\text{HP: } \frac{0.00399 \times 1.7 \times 256}{4} = 0.425 \text{ HP}
\]

Total: Adder + Torque = 0.825 + 0.67

If each segment mass \( 0.1 \text{ HP} \) or \( 0.425 \)

\( \text{in the paddle} \frac{0.425}{4} = 0.64 \)

\( d = 2.78 \quad 12 \)
3 M.P. @ 20 rpm.  

- 10" Dia. Chain velocity:

\[ \frac{\pi \times 10 \times \frac{10}{12} \times 20}{52.3} \text{ ft/min} \]

\[ \frac{3 \times 52.3}{32000} = \frac{33000}{32.3} \]

Minimum Chain 6" pitch, 2000 lb.

Chain No. 80

Pitch 1"  
Roll dia. .625
Breaking load 17,500  
Wt./foot 1.68

Load capacity at 25 rpm 2.639 with 39 ft.
EXHIBIT B-5 (Cont.)

Torque Tube

Material: 304 Stainless

O.D. = 2 3/8"
I.D. = 1 93/16"

Torque 8,500 in-lb

\[ T = \frac{J\omega}{2} \]

\[ J = \frac{\pi}{2} (D^2 - d^2) = \frac{\pi}{2} (32^2 - 13.5^2) \approx 65.1 \text{ in-lb}^2 \]

\[ \omega = \frac{8500}{\frac{\pi}{2} \times \frac{14}{32}} \approx 1768 \text{ rad/s} \]

\[ F = \frac{8500 \times \frac{14}{32} \times 1.975}{1768} \approx 5700 \text{ psi} \]
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In addition to the above stock range, sprockets in other sizes and for double, triple and quadruple strand chains, are available to order.

### REBORING, KEYWAYING AND SETSCREWING

Stock Sprockets and Couplings

#### BORE TOLERANCES

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#### KEYWAYS and SETSCREWS

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<th>Dia. of Keyway Screw</th>
<th>Shaft Diameter</th>
<th>Keyway Width &amp; Depth</th>
<th>Dia. of Setscrew</th>
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*Keyway width tolerances are plus 0.002 minus 0.000; keyway depth tolerances are plus 0.015 minus 0.000.*

*Standard taper keyways are 1:8 for shafts. Taper keyway width tolerances are 0.000 plus 0.003 minus 0.005.*

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Sheet 3 of 5
### RENOLD Single Strand Roller Chains A.S.A.

For further dimensions, see Designers Data Sheet – page 38

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<th>Roller diameter</th>
<th>Bushing diameter</th>
<th>Between roller link places</th>
<th>Chain track</th>
<th>Nominal bearing area</th>
<th>Breaking load</th>
<th>Weight per foot</th>
<th>Ronald Chain No.</th>
<th>SPARE PARTS AVAILABLE</th>
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* Rollerless chain

† See Data Sheet page 38 for definition

### SPARE PARTS

- No. 6: Roller link
- No. 107: Pin link
- No. 36: Connecting link
- No. 37: Spring clip
- No. 38: Top and bottom offset link
- No. 39: Connecting link
- No. 57: Double crown
- No. 59: Crown link

Sheet 4 of 5
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- For load ratings, see page 13.
- For Contact Seals — use suffix "C".
- Oil holes available in Millimeter Bores, see page 58.
- Lubrication fitting on front face of casting.
- Outside diameter tolerance .000 — .005.
- For load rating, see page 12.
Design of a Creme-Lite Mixer (C)

While Harry Anson was busy detailing the mixer and preparing the drawings, George addressed himself to Webb's inquiry about cooling the fat from 130°F to 80°F (Exhibit C-1).

For the analysis, George assumed that the cooling water temperature would be at 70°F, 10° below the required final temperature. As expected, the temperature was found to decrease exponentially. Some searching was required to determine suitable values for the specific heat of fat $S_H = .64$, and for the coefficient of heat transfer at the water interface $h_o$ and the fat interface $h_i$.

The cooling time was found to be approximately 6 hours. Even with errors in the approximations for the heat transfer coefficients, this indicated that the fat could be cooled readily during the night shift. This information was passed to Webb at West Ltd.

Harry Anson completed the detail drawings of the tank (Exhibit C-2).

---

(c) 1969 by the Board of Trustees, Leland Stanford Junior University, Stanford, California. Prepared for the Stanford Engineering Case Program by G. Kardos, Associate Professor of Mechanical Engineering, McMaster University, Hamilton, Ontario, Canada, with the support of the National Science Foundation. Although names of individuals and firms have been fictionalized, the case is based upon real engineering activity.
Before releasing them to the shop for manufacture, George checked them carefully to ensure that they met all the requirements. Harry had done an excellent job. Only a few minor additions were required. One of special note is the scraper assembly on DE-1: Harry had located standard hardware "Burndy Nyloclips" to attach the scrapers instead of having special attachments made as had been expected.

The tank was fabricated by the shop. During fabrication, the shop, from its experience, added additional bracing to the legs. This was a point both Harry and George had missed. The addition added to the rigidity of the structure.

Before the tank was completed, Charlie and George went down to the shop to inspect it. They noticed that the welding of the pan containing the chain drive was discontinuous and on the inside. This was in line with accepted economical structure welding practice. But in this case it was unsatisfactory as food handling equipment. To prevent contaminants entering the fats, they asked the shop to put a continuous bead of weld on the outside of the joint.

The inspection also brought to the shop's attention areas where the welding had not been properly ground flush. These were re-worked. The shops hadn't any previous experience with food handling equipment and had a tendency to fall back on standard commercial practices.

George was now on his way to G. West Ltd. plant in response to Charlie's telephone call. Something had happened to the mixer. It had been installed only a couple of weeks earlier. George later related to Charlie what had happened.

"When I arrived at the plant, I was taken by Webb directly to their overhaul department. The gear box was apart. During the first trial of the mixer, the gear box had failed. Webb showed me the bearings and the worm from the box; they were badly scored and obviously had failed from an overload."
"Webb informed me that he had had the 'Crofts' representative in. They had concluded that the gear box had failed due to overloading. They had concluded that 5Hp. motor with 3 to 4 belt drive would overload the gear box. Webb virtually accused me of having engineered it incorrectly.

"I was in a rather tight spot. I knew what was happening, but I had to explain it to Webb in a manner that he could comprehend and accept. He was obviously in a mood where he wanted to saddle us with all the repair charges.

"I told Webb that I agreed the gear box failed from overload. Then I pointed out that the 5Hp. motor had been chosen because of its availability. I stated that even at the 20 rpm requirement, the mixer would only draw about 3Hp., not enough to overload the gear box.

"I tried to find out whether the fat had been allowed to cool below 80°F or if mixing had been stopped for any reason. He assured me that it hadn't although from the vagueness of his reply I am certain it had. Of course, with Webb being the customer, I could not afford a direct confrontation. This was where it was less important to be right than to satisfy him.

"I assured him that at the actual operating speed, 15 rpm, the paddles just could not draw the necessary horsepower to overload the gear box. I inquired if a motor current reading had been taken during installation. Webb admitted they had taken readings with a 'clip-on' meter and that the current was negligible. I pointed out that this indicated that the motor was not running anywhere near full load.

"We were at a impasse as to fixing the blame. Therefore, we turned to the more important task of what to do to put the mixer back in service and prevent the failure from recurring.

"The gear box could be repaired by replacing the bearings. With a little pressing, Webb agreed that from their limited running experience the 15 rpm mixing speed
would be satisfactory. Webb also stated that their maintenance department had electric motors of various sizes available and the replacement of the 5 Hp. motor with a 3 Hp. motor could be readily done.

"It was then agreed that the unit would be put back in service with a 3 Hp. motor. I suggested that the motor be fused so that if more than 3 Hp. load was generated the fuse would blow.

"Webb and I agreed that if operation of the mixer caused the fuses to blow, the design must be faulty and Roche Inc. would replace the gear box with a larger one. If the mixer functioned satisfactorily, the design must be satisfactory and no further action would be required on the part of Roche Inc."

George and Charlie informed the general manager of Roche Inc. about what happened at West Ltd. Nobody was happy with the situation, especially the prospect of having to replace the gear box.

Nothing further was heard from Webb. Charlie has had no occasion to call at G. West Ltd. since. The mixer is in service and operating satisfactorily. It can only be assumed that on the initial trials, the fat had been allowed to crystallize and in attempting to start the mixer up again, the drive system had been overloaded.


**Heating Time**

\[ T_0 = 70^\circ \text{F} \quad T_i = 130 @ t = 0 \quad T_f = 80 @ t = ? \]

\[ Q = \frac{dW}{dt} = U (T - T_0) \]

\[ H = W \cdot S_n \left( \frac{T_i}{T_0} \right) (T_0 - T) \]

\[ \frac{dH}{dt} = W S_n \frac{dT}{dt} \]

\[ -W S_n \frac{dT}{dt} = U (T - T') \]

\[ -\frac{dT}{(T - T')} = \frac{U}{W S_n} dt \]

\[ -\int \frac{dT}{(T - T')} = \int \frac{dt}{\left( T - T'_0 \right)} \]

\[ -\ln \frac{T - T'}{T'_0} = \alpha \int \frac{t}{t_0} \]

\[ -\ln \left[ \frac{T - T'}{T'_0} \right] = \alpha \left[ \frac{t}{t_0} \right] + c \]

\[ -\ln \left[ \frac{T - T'}{T'_0} \right] + \ln \left[ \frac{T_0 - T'}{T'_0} \right] = \alpha \left[ \frac{t}{t_0} \right] + c \]

\[ \ln \left[ \frac{T_0 - T'}{T'_0 - T'} \right] = \alpha c \]

\[ c = 0 \]
\[ \frac{\tau - \tau'}{\tau_0 - \tau'} = e^{kt} \]

@ \theta = 0 \quad \tau - \tau' = \frac{\tau_0 - \tau'}{\tau_0}

@ \tau = \tau_0 \quad \tau - \tau' = 0

\[ \ln \frac{\tau - \tau'}{\tau_0 - \tau'} = -\alpha t \]

\[ \ln \frac{\tau_0 - \tau'}{\tau - \tau'} = \alpha t \]

\[ \ln \frac{\tau_0 - \tau'}{\tau - \tau'} = 60^\circ F - 70^\circ F \]

\[ \ln 60 = 1.79175 \]

\[ \ln 10 = 2.30258 \]

\[ \alpha = \frac{1.79175}{2.30258} = 0.77 \]

\[ \ln 60 = 1.0983 \]

\[ \ln 10 = 2.30259 \]

\[ \alpha = 0.77 \]

\[ W = 5400 \text{ ft} \]

\[ \frac{\theta}{\theta_0} = 0.84 \]

\[ \theta = 8 \times 15 \times 5 + \frac{27}{\frac{5}{3} \times 5^2} = \frac{27}{\frac{5}{3}} \times 25 \times 25 = 935.2 \text{ ft}^2 \]

\[ u = \frac{1}{h_0 + \frac{1}{h_1} + \frac{1}{h_2}} \]

\[ h_0 = 300 \]

\[ h_1 = 10 \]

\[ h_2 = 1875 \]

\[ K = 105 \]
\[
\frac{1}{y} \cdot \frac{0.025}{105} + \frac{1}{300} = 0.003 + 0.0018 + 0.1 = 0.1048
\]

\[\alpha = 10 \times \frac{100}{3 \times 6} = \frac{10}{18} = 0.29\]

\[1.79175 = 0.29 \times t\]

\[t = \frac{1.79175}{0.29}\]

Say 6 km.
Appendix B

Hospital Bedside Computer Terminal

by Gibson Product Design

This is the raw transcript of a meeting, on Wednesday 17 March 1993, between Scott Gibson and Ross Cowie, discussing Gibson Product Design's involvement in a design project. The product was a bedside computer terminal, to be manufactured by Digital, for a hospital consortium client.

Ross Cowie: If you can describe the project briefly, which for me, is, if I am starting with zero knowledge of your project, you can start telling me what you learned early, and that becomes my initial knowledge of your project, and then I know I can, ...

Scott Gibson: Right, well I'll just give you a brief history of how it came about. We were approached by a couple of engineering guys from Digital Equipment out in Kanata, this is a small product development group that is more of a consulting group than a full-time product development group, in that they tend to respond to the needs of customers who are looking for a special feature or a special characteristic that is unavailable in the standard Digital catalog of components, computers, cabinetry, whatever, and the group that we encountered, gets brought in where Digital's standard stuff doesn't meet the requirements, and there is some special work necessary. In this case, the special work necessary was to develop a terminal.

RC: For a third party?

SG: For a third party.

RC: Which is where the requirements are coming from?

SG: That's right, and in this case the terminal had a specific application and that was to be a bedside terminal for hospitals. The fact was that nothing existed on the market from any vendor that would fulfill the requirements that this third party perceived. Digital said, "Well, we'll go ahead and develop one for you, why don't we do that?"

RC: A bedside terminal is essentially the, ..?

SG: Yes. And through negotiations, the third party came up with a budget, and figured that would be a reasonable approach. So, Digital then began, the engineering guys began, the product definition cycle, and had actually got a little bit into product design, in other words they had gone out and hired some illustrator to, you know, create some
pictures like the one you see on the wall, depicting a kind of a hospital situation, and depicting the ideas the Digital guys had come up with at the very beginning.

(examining picture hanging on the wall)

RC: This picture, was this early, or is this final?

SG: This is final. An operating terminal, and everything there is real, except the patient, who is a Digital employee, and he is not sick!

(Both laugh)

RC: Right, okay, but the initial product that the illustrator provided was a similar picture to this, but it wasn't that terminal and these people, but it was a patient, a nurse, a bedside?

SG: That is right, and the illustration incorporated the ideas of the engineers which had emerged in discussion with the...

RC: Okay, so what had they...? So by the time you got it, they had done some work on it?

SG: That's right. Yes.

RC: So what had they learned, or what had come of their work?

SG: Well they had determined that they needed a display screen, and a keyboard, and perhaps a bar-code reader, they had gotten to the point, where a bar-code reader seemed...

RC: A maybe?

SG: ...seemed to be a very good idea, and as the project moved along, that idea quickly became locked in. There were also issues of how to mount this thing, where to put it, in the patient's room, because this in the photograph, it hits at a battle for territory around the patient's bed, and therefore one of the earliest design criteria was the need for a very small footprint. Or even better, something that would mount on the wall, on a swing-out arm, or pull down from the ceiling, or something, so they could just get it out of the way, when it is not in use.

RC: The photograph shows a swing-out arm.

SG: Shows a swing-out arm, and that is one of the ways. It is also perfectly capable of sitting right on the little side-table, anything like that, any means that is convenient
and economical will suffice. The terminal is a stand-alone unit.

RC: This was an early consideration, that it would have to compete for space? And that it would have to fit in the typical, or expected spaces, at a bedside?

SG: Yes. And so what they had, their initial concept was that there would be a, this sort of a revved-up wall bracket thing that actually sticks right on the wall, and then there would be, I think it was a clip-on keyboard, and a terminal with a, or a display screen rather, with some kind of hinging, so that it could be brought up and stored up against the wall, or brought down and matched up with the keyboard, and therefore provide some security against unauthorised use of the machine.

RC: By closing or covering up the keyboard?

SG: Yes. Right. But it was very, very, loosely worked out, and it was only intended to again, get feedback from the customer. The customer was a consortium of hospitals who were buying some software from a software developer in Quebec, the S!OC!S, the societee something or other. Anyway, so they were in the stage of giving and receiving feedback on their original product definition, and they came to us to make the model, that is all that it was. So we were delighted to get the work, and went ahead and made them a model, but in the process of looking over the drawings, we realised that what they had there, would never, would never stand up mechanically. The hinge and stuff was appallingly weak, and so we made some suggestions.

RC: But these were engineers who had?

SG: Yes, yes they were, and very good people too. I can't help thinking now, though they'll never admit it, that they put that in as a test, to see if we could throw in our expertise, or to see if we had any expertise. I don't know, they were very cagey, and very clever about the way they went about engaging us.

RC: An interesting sidebar.

SG: Yes. So anyway, we made some suggestions about how to change it, and they said, "Well, okay, go ahead and do that." So we did. and we made the model, and they were delighted, and that was the end of what you might call Phase Zero, as opposed to Phase One, because the next step was that they came back and said, "Nah, we'd like to develop the proper product, we've got more information, and we would like to involve you in the design process." That was of course our true Stage, or Phase One, which was concept development pretty much from zero.
So the old model was thrown out, and that became just an idea generator more than anything.

RC: Okay, but I assume that the model was discussed obviously by the customer, to get
at what did we learn positively from it, what did it tell us that we are doing wrong, and that sort of thing?

SG: That's right, and so it paid for itself.

RC: It got you the job!

SG: Well, yes. We proved that we could build a model, that was all, but we also proved that we had some brains, and we could think about things, and so we had a lot of ideas.

RC: Did some of those ideas go into that first model?

SG: Well the ideas of how to make the thing mechanically sound sure did, but we were not in a position to offer design solutions because we had no information. All we had basically was "Make this."

RC: Yes. But you obviously added, with your knowledge, to what was given to you, and gave them back something that probably would have looked better than what was given...

SG: Yes. Well it wasn’t just looked, it functioned better, and there were some manufacturability issues in there to, which we also accounted for, and so the model that they got combined mechanical, congruity, and manufacturability from a very, very preliminary point of view, but it still was there.

RC: This is interesting in light of concurrent design, where you are talking about manufacturability issues, but you are talking about this model as Phase Zero. Even from the start, production issues, manufacturability issues, have gotten into there.

SG: Always.

RC: Always, and I agree they should, but that is very much counter to the idea that you start from concepts, and somewhere down at the very end, you are working on production drawings, or production concerns.

SG: Oh no, no, no. That's a cardinal error, if you think that. Concepts, right at the very beginning, concepts must take into account manufacturability. Concepts, people, when you're developing a concept, you're looking for boundaries. You can't develop a concept without boundaries, it's impossible. For example, somebody says please design me a box, the first question is "How big?", therefore you've created a boundary right away, and the more knowledgable you are, about the particular situation, and the more knowledgable you are, from your own background and experience, the more boundaries you create, right at the beginning. And you want them, it's not a downer to get a bunch of boundaries, it's the best thing that could ever happen to you, because no
matter how many boundaries you’ve got, you’ve still got lots to room to play, and get your design rocks off, and that sort of thing, if that is what you need. And so, we’re looking for boundaries, and manufacturability is one of those things that I jump on immediately. It’s interesting that you should say that, because one of the great fears of first time out engineering guys encountering Industrial Design, is “Oh God, they are going to give us something that we can’t make.” I hear it all the time. And I’m astounded to hear this, because I don’t know where it is coming from. It might have come from some mythology passed on down the line, that they learned at school, or they read something, who knows, but no Industrial Designer worth their piece of paper would ever propose anything that is not manufacturable, it just doesn’t happen. It is simply a non-issue.

So, concept is not as wild and woolly as you might think.

RC: But I think that is a common misconception among students, and perhaps Industrial Designers coming from a fine arts background, where...

SG: No Industrial Designer comes from a fine arts background. Well, I should say, all Industrial Designers share a common knowledge base, and whether they come from a fine arts school or an engineering oriented, like Carleton, type school, they still have that knowledge base, and that includes manufacturability. Maybe you are encountering somebody who claims to be an Industrial Designer who isn’t, and is quote "An Artist" or something else, but they are certainly not an Industrial Designer.

RC: Okay, if anything, I think that it is a clash between your definition of what an Industrial Designer is and should be, and perhaps another person, perhaps the student’s idea of what an Industrial Designer is, or a misconception, an engineer’s misconception, of what an Industrial Designer is or isn’t.

SG: Yes, that is what it is. All you have to do is pick up the ID annual, which I presume you do, or ID magazine, and read it regularly, or even better innovation from the IDSA, their magazine, and you’ll realise that this is no fine arts activity at all, at all. It’s a product development activity, to be taken as seriously as engineering, or marketing, or finance, or any other aspect of product development. It’s not airy-fairy, it’s not guys with berets and magic markers, it never has been, it never will be. In fact it’s moving more and more towards taking in the engineering and marketing aspects of product development. Very good designers can do it all. They can also do fine art if they want, but they are not pigeon-holed as quote "artistes". Usually a guy like, the great French designer, Philippe Starck, who is seen as a very high style designer, and probably on the surface of it, fitting the definition of a fine artist, doing design; even a guy like Philippe Starck is looking at manufacturability, in a very focused way. He may use exotic processes and exotic materials, and challenge the capabilities of manufacturers, but none of these products get out on the street without being economical.
RC: I find what is interesting, I’m looking at a book of finished products. What I’m not looking at is a book of drawings or concepts, which have not progressed to the stage of being manufacturable, and it is possible, obviously, to make a mark on a piece of paper which does not describe something realisable. This is my complaint with...

SG: Nothing goes out the door without his approval.

RC: Un-huh. My complaint perhaps with even the architecture, uh, as it seems to be, as I see it in the hallways at Carleton, there’s a lot of fanciful ideas that you wonder about the ultimate realizability.

SG: Of course. And it is structured that way to force students to expand their imaginative field. That, they do it in Industrial Design too. It is done more in other places than it is done at Carleton, because imagination is a critical element, but imagination must work within the bounds of do-ability, or you can’t earn a living at it. And that is really the bottom line.

RC: Okay, being conscious of your time, getting back to the project. So we were at, you were involved at say Stage One, getting into, I think this is where we left of the discussion of the project specifically, you were called in on Phase One in fact to develop concepts, after the model.

SG: Yes, that’s right. So the model became a background to the whole thing, it was more an introduction to us than anything. So the performance criteria were such things as product security, ease of use for untrained, people that aren’t computer literate, since it would require a tremendous learning curve to bring a product into the health care environment that required dedication of time and the inherent errors that would go hand-in-hand with a new type of activity for them. So ease of use in every way, ease of comprehensibility, non-threatening type presentation to the users, a non-threatening type presentation to the patient as well, were all factors. Then the functionality issues, data input and output were discussed, how were we going to interface with the computer system, which the terminal does.

RC: When you looked at that input/output, how much of it was the hardware side, and how much of it got into the software side in depth?

SG: Most of it was hardware, because the software was essentially in place.

RC: It was in place already?

SG: Yes, essentially. It was a Beta version, it was sketchy, but they were trying to...

RC: And this was being worked on by the customer?
SG: Yes. A lot of the product definition information was coming from the customer, which it should. The Digital guys were essentially filtering that from the standpoint of economics. I'm sure that if the hospital consortium had its way, it would have been quite well loaded down with features, but it would have been too expensive to produce, so that type of negotiation brought the list of features down to a workable number of features, and very early on we had that information. What they wanted was a backlit liquid crystal display with a touch screen on it. They wanted a bar-code reader; that became locked in. In fact, the bar-code reader evolved into two bar-code readers, one for cards with a slot to run the cards through, and the other would be a wand reader, which would enable them to expand the bar-code applications to reading the patient's identity from their wrist bracelet, or reading medications, and so on.

RC: When they asked for these items,

SG: I'll just finish. Then, keyboard. Those were the input/output devices that everybody agreed could be achieved in the price range.

RC: Okay, I'm just wondering, how much of why they wanted a touch screen and an LCD display, was given to you or was that as much as; that's the requirement, that's what were we working with.

SG: Well, the rationale was fairly easy to understand. There needed to be a display. The size consideration, the real estate consideration said that it couldn't be a CRT, therefore the only economical alternative is an LCD, and the backlit feature comes from the working environment, where you are working at any time, night and day, and therefore you don't want to have to switch some lights on.

RC: Just what I'm trying to clarify is that these are considerations that the customer and Digital had discussed, and looked at a few options, but the obvious decision taken was...

SG: And it wasn't hard to arrive at.

RC: Easy or not, that was one of the things that had to be decided, which is the only reason I just wanted to...

SG: Un-huh. The more critical phase was having decided that these were the generic devices, was deciding the specific ones. Again, we couldn't go about developing as Macintosh might, or Sharp, or any manufacturer of finished products. We couldn't make a custom liquid crystal display.

RC: The LCD screen decision was easy, but then it was which one?

SG: Yes, which required a bit of research, and it was narrowed down to maybe a couple of choices, but eventually we found that the size profiles were very close to each other,
so that was only a matter of can we get them, when, what price, etc. A choice was made, and there was the display. At that point the physical envelope was beginning to form. We had what they refer to in the car design business, we had hard-points, that we had to put a skin around. We were getting to know what the things were.

RC: Between the final two or three LCD screens you looked at, what ultimately was the deciding factor that governed the ultimate choice that you did make?

SG: Oh, three things, price, performance and physical size.

RC: So the one you chose was a little smaller, and that worked better, or was it more standard, or?

SG: Actually, they were all about the same size, and it was the price/performance. And it was Digital's call.

RC: And it was performance in regards to?

SG: Refresh rate. The life and the general luminescence of the screen, the light level. Essentially that. They get into particularly the refresh rate, because if you are scrolling information on a screen, you know what happens on a liquid crystal display, it all kind of goes blurry, because the screen can't re-generate itself quickly enough.

RC: So refresh rate became an important consideration.

SG: Oh yeah, because they understood what the application was going to entail, and it was text, and there is also a windows type display, where in using a touch screen, you wanted it to react to your finger motion in a natural way. Human factors considerations.

RC: This is tying very much back into knowing who the user was, and the user environment, and...

SG: And what was to be displayed to help in their work. It came down to a display by Sharp, and it was available, and we could get it in sufficient quantities, a 16-week turnaround.

RC: So there were no negatives on availability, delivery and so on? Which would have perhaps disqualified it. If it had some other unfortunate other baggage tied to it?

SG: Un-huh, yes. The keyboard, again there were two constraints here, size, and the other was its ability to stand up to being cleaned in the standard hospital fashion, which is to kind of swab it down with an ammonia solution, and therefore the key technology, the switch technology, had to be of a sort that could stand up to the liquid ammonia. It was a Hall-effect switch, which has a sealed contact, and you can virtually put the thing
under water and it will work. It's a little more expensive than other technologies, but it would do the job. But again, it was off-the-shelf, except for some modifications to the metal work.

RC: The metal work of the keyboard?

SG: Yes. The keyboard always comes in a frame, and the standard ones had outrigger bolt-down positions, and we didn't want that. We wanted to get this thing in as tight as we could. We wanted the package to be as small as we could, I say we, it was essentially Digital, but under our advice. We went to the supplier, and they did a special.

RC: Did you end up mounting it from underneath? So this is to get the total width down?

SG: Yes. But even then, as far as miniature computers go, or in this case a terminal, it is still pretty wide. We could get it down closer, but at that point you are getting into a custom product, and we were buying the stuff from off of the shelf.

RC: There was no trade-off in height, with the mounting procedure that you used?

SG: No.

RC: So it was something you got for free.

SG: No, it was an additional cost.

RC: It was a cost, but a cost over the standard keyboard, its an alternate mounting system; but in terms of width, height, other performance, it didn't affect it.

SG: It didn't affect it at all.

RC: You got a smaller width, and no increase in height, or volume, or?

SG: Yes. I think they have actually standardised to it.

RC: That was because it was a good idea?

SG: Yeah, and well nigh due. These guys were back in the sixties with their big metal frame and that's the way things used to be, but it is certainly not the way it is now.

RC: Well, good.

SG: Yeah, in a lot of ways they gained from having done that product. Now they've a catalog sheet out on this keyboard.
RC: Great.

SG: Other things; the bar-code reader. At first we thought we were going to have the bar-code reader as an external block, and just buy it off-the-shelf, prepackaged and ready to go. That would have been a disastrous solution, because then you have to put the thing somewhere, and you’ve got two pieces instead of one. It turned out that the manufacturer of that particular bar-code reader was quite happy to do a special run with no packaging, and mounting the electronics and the optical stuff on a special set of aluminum extrusions that we designed. The extrusions then dropped right into the housing.

RC: So he’s giving you a module, or a chassis almost, that you could then put your own packaging on.

SG: Well in fact we gave them the chassis. We designed the aluminum extrusions, had them produced, and sent them down to the bar-code reader guys, and they mounted their stuff in the extrusions.

RC: So the interface between their stuff and your stuff was the shape of this extrusion, and they fit it to your extrusion?

SG: Yup. That’s right.

RC: And then you knew that your extrusion would also fit where you wanted it to.

SG: Yes, because that’s where it started.

RC: Now this is the swipe-card bar-code reader? I don’t see it on this picture on the wall that I’m looking at. Is it on the right side?

SG: No, it’s up in the hinge area, on the right side of the hinge area. You can see the slot there?

RC: Ah, okay, I see.

SG: So that was a bit of clever design, along with negotiation and a real willingness on the part of the bar-code technology suppliers, to cooperate on this thing, and it worked out very well.

The touch screen is the thing that goes over the liquid crystal display, and it’s a separate piece altogether. It’s like a little membrane that sits in front, and that had to be custom designed, pretty much from the ground up. Digital was unable to find a supplier of touch screens for that particular display, and there is not a huge demand for touch screens for small displays like this. The supplier developed it from zero. The touch
screen electronics was developed by a company called Micro Slate in Montreal. There was a three-way play: there was the printed circuit board size, which had to be packaged, there was the touch screen technology itself which was being developed, and the ___ had to interface with the electronics, and then there was the packaging design group itself. So the three of us had to work together on that, and there were many issues that had to be resolved. There was gasketing around the plastic facia and the touch screen, because we couldn’t have liquids getting in there from the cleaning process. Simply the functionality of the thing, the number of pixels that had to be addressed by a touch. From that technical level, there was the interfacing of the touch screen outputs with the mainframe computer switch addressed by the terminal.

RC: So it’s interesting that, the three way, the actual touch screen manufacturer, was not the people working with the electronics of the touch screen, and the people working with the electronics were not Digital.

SG: No. So the FAX machine really comes in. In fact there was the industrial design input, there was Digital’s input, there was Micro Slate’s input, and then there was the manufacturer of the touch screen. Just in that one area there was a very interesting interplay, and it worked quite well. There were adjustments to be made as the process came along, very fine tuning at that point. Maybe I’m getting a bit ahead, because this stuff was happening just prior to going to hard tooling for the plastics. We’re still back in the concepts. There were many stories that ran concurrently.

RC: And the area that we’ve been talking about is a little bit toward later in the process.

SG: Yes, once the dimensional information of the package was getting nailed…

RC: That had to happen first. You had to select the screen first, before you get onto the touch screen, the LCD screen.

If we get back onto sort of a time line, in a lot of these issues, you’re obviously discussing them in the conceptual design. Were there intermediate, specific intermediate, stages where major decisions were made? Is there a Phase One to Phase Two transition somewhere?

SG: Well, Phase One is concept development, where you are pulling in as much information as you can. By the end of Phase One we had pretty much enough dimensional information that we could say, “This is the concept”, and nail that thing in terms of illustration and a good first model.

RC: Okay. What’s resulting, or what you knew or had available at the end of what we are calling Phase One is: you had another model, several models?

SG: That’s right, we had done several models. We didn’t do a good presentation model
until the end of Phase Two. The end of Phase One we did illustrations and ...

RC: Quite a number of them? I’m trying to get an idea sort of, of the quantity, and the names or types of information you had at the end of Phase One.

SG: At the end of Phase One, we were able to show presentation illustrations that showed a lot of detail, and gave the customer, Digital, a very good impression of what the product was going to look like. Of course they knew that already, but there was management that had to be shown this. The engineering guys that we worked with, it was hand and glove all the way.

RC: You had been discussing these topics all the way?

SG: Oh yes. We didn’t go away and then surprise them.

RC: Yes. Getting back to quantity, where in what I’m looking at, I’m trying to sort of trace, in a way, well obviously we go from abstract to detail as we’ve discussed, but you also go from lesser amount of information to more, so when you say you had some illustrations, and you started with an initial concept model, well now you have illustrations of the end of Phase One. I’m assuming you have what ten, twenty? Sketches, poster boards? What form are they?

SG: They range from thumbnail sketches, little things, to a first crack at a layout of all the components, to try to create a reasonably accurate notion of the physical size of the thing. And moires, and sketches in the package there, in the archives. The sketches are of that level there, that complexity, (pointing to illustration on the wall), that I call thumbnail. And then final illustrations are renderings.

RC: When you presented to management, I take it there must at some point, either you, or you and the Digital engineers presented to management. This is what we are talking about as the end of Phase One, essentially this presentation to management of work to date. That presentation, did it include slides, or any other...?

SG: No. Not in this case. It just included a general round-table discussion, a written report, and the illustrations.

RC: A written report. Of?

SG: A progress report. Three pages, this is what we have done, and next steps. The intent there was to create a smooth transition to Phase Two, which was the design finalisation.

RC: So the next steps, the design finalisation. What at that point had been finalised after
that meeting, or shortly after that meeting, and what was the work of Phase Two, if you
can describe that?

SG: Sure. Well, the end of Phase One, essentially communicates that this is our intent,
this is the way we see the product. We believe that, generally speaking, what you see
here is what you’ll end up with at the end of the program, with the understanding that
more information will come in, some details might change, but generally speaking, we
are doing this, we are not doing some six foot high cupboard. It’s an opportunity for the
management guys to ask questions, to make their input. Phase Two then becomes the
creating the hard definition of the design, which will stand as the measure, against which
all of the other people involved in the process will test their aspect of it. For example,
the electronics guys will then know exactly how much room they have to put the boards
in. That is not to say they have not had any input before, but now everybody knows that
it is going to be 8.35 inches is what you’ve got.

RC: So is that making the hard-points a little harder? To greater accuracy?

SG: Yes. Well, the hard-points are, the way I’ve described the hard-points is when you
have a bought-in piece of stuff, that you can sit on the table and measure, that is a source
of hard-points. Circuit boards have some flexibility, you can change the shape of a
circuit board to accommodate something. The circuit boards were being developed, and
in order to nail the dimensions of the circuit boards, all of the other components had to
be put in place, and tested as to their suitability for working the circuit boards around.
For example, if you decided to stick a fan right in the centre of the lower portion, or
something like that, nobody is going to circuit boards with a great hole in the centre of
them. So the suggestion there would be could you please move this thing?

RC: So as the hard-points get harder, you’ve made a decision that the circuit board is
one of the last hard-points to make hard, because we know its flexible. If we take the
LCD screen, which we know we are buying from a supplier, and it has certain mounting
points, those are the hard-points, that’s the first hard-points that are fixed. Other items,
similarly sourced, that are not custom, have their own hard-points, and then you work
through the list, trying to define all the hard-points. What you are saying then is the
circuit board doesn’t have as hard a hard-point as the LCD screen, because you’re
making the thing, and you know you can move it?

SG: The same goes for the outside package, of course. It’s, in a lot of ways, the last
thing to go.

RC: And it needn’t be any bigger than what it needs to hold. And can’t be any smaller
obviously.

SG: Right, right. Other things driving the final dimensioning were user standards for
keyboard height and slope, not that this product is used very much in a classical speed
typing application, but in the European market, the keyboard has to respond to certain dimensional requirements.

RC: It's interesting that you mention the European market. We haven't discussed the market for this product. The intent is world-wide?

SG: Yes, the intent is. No one makes anything that is not going to be sold as widely as possible.

(Tape change)

SG: The deliverable at the end of Phase Two is what I would call a set of design intent drawings which define the outside dimensions of the product and there are some section drawings showing location of the components in the thing, but still, we don't have dimensioned drawings at this point.

RC: But the drawing you have doesn't look appreciably different than some of the earlier concept drawings?

SG: No. Now they look totally different, because now they are drafted.

RC: Ah. Okay. I was going to say, they are still of the same product, obviously, and there will be things that look the same, except obviously the refinement of this drawing, is to a higher level of refinement, and the changes, the decisions that you have made about changes from earlier concepts, are incorporated. You can still see the genesis, I mean you're not now talking about a six foot high cabinet.

SG: Anything but. Now you are down to decimal points.

RC: In this, at the end of Phase Two, the drawing that you are supplying, has lines positioned, not dimensioned, but lines are positioned much more accurately?

SG: The external dimensions, the general dimensions, are nailed, as much as possible. It is not to say that they are not open to tweaking, but generally speaking, it is saying that this is what we have committed to now, and we know that we can make this work.

RC: So where the concept drawings had no dimensions, these drawings have some dimensions, but you are making the point that they are not fully dimensioned.

SG: That's right. They are not manufacturing drawings. Nor is the internal detailing of the product set.

RC: Okay. I'm just trying to place these drawings in the refinement from abstract to detail. We are at a certain point.
SG: Yes. We are at a benchmark point.

RC: More than this, less than that.

SG: Yes, this is in a lot of ways where the tooling designer mentality comes in, because now we have got some real tight boundaries, and within those boundaries, we work to do the refined detailing. That is the bosses, the snap fits, all of the stuff, the plastic parts in this case, but we don’t go beyond those boundaries. We do look to see where we have clearances and where we have not got clearances, because we can see now where all of the components go. There may still be some latitude to bulge a circuit board half an inch into a space because nobody is taking it up yet. There is still territory that is available, and there is territory that is not. It’s defined. The other deliverable is a non-functional presentation model, which in this case, was done in the contracted out model-shop that we always use. They machined it.

RC: Other than obviously this model incorporates some decisions made since the first model, so that it is different in that way, but in terms of the nature of it, in refinement, if we can place it on the scale from abstract to detail, you know, final production casting, what are the differences?

SG: Oh. It’s very much advanced. It should be very much advanced, and the differences between that model and the production piece should be very minimal.

RC: So this one, where the earlier concept model that you produced in Stage Zero, it would not have all the lettering, it would not have those things.

SG: Oh no, in fact it was made of foam-core. Very simple volumetric studies, that is the only thing. In concept development, there was a need to look at the thing in 3D, and get a feeling for this totality of the thing in space, as opposed to illustration, where you can show a plan, or make a 3D illustration, show it in elevation, or whatever. You don’t get a sense of it, like you do with a volumetric model. There was no attempt in Phase One, in terms of modelling, to nail all of the additional details.

RC: Okay. When we talk visual detailing, this is just what I’m trying to describe. So now, to the level of the model that we have now, you’re obviously very concerned with making it look the way the finished one should look, in terms of colour, all the details, lettering, switches, it’s non-functional, but otherwise, from appearance, it should appear as if it could function.

SG: That’s right. And again, it is only a model. It is there for study. The purpose of it is to show to all of the interested parties, including the hospital consortium, and the software guys, the manufacturing guys, the guys at Digital, the management guys, the engineering guys and ourselves, and the marketing guys at Digital, too. They were very interested, and wanted to start taking pictures right away, and cranking out brochures,
which is a reasonable thing to do. They can get a real jump on the development process, because it will be another six months before the first moulded parts, at least six months. So, like I say, the end of Phase Two is the expression of design intent. I think that is the best way to put it. What you see is what you are going to get. There is a very concerted effort at that point, to make a design freeze. No more major changes. We are not going to stick a handle on it. We are not going to change it's overall changes. This is, in fact, if everybody agrees, because after that, Phase Three is Manufacturing and Development. At that point we get into taking this model apart in effect, and taking each of the components that make up the thing, and preparing the manufacturing drawings, which are fully detailed, in every way, geometric tolerancing, the works. That's Phase Three, essentially creating the manufacturing and documentation package which involves the plastic parts, the circuit boards, the aluminum extrusions, the mechanical devices which are Belleville washers and springs and so on for the hinge, CNC machined steel, etc., etc.

RC: Giving everything part numbers, and making drawings of assemblies, all of that.

SG: Yes, all of that. Phase Three then is the big phase, it was a monster, on everybody's part. The engineering guys were working hand and glove with us, but we produced all of their manufacturing drawings. That is not always the case with Industrial Design, but around here, it has been the most prudent way for two reasons. It is hard to find someone else that can do it, and it is the most profitable, in many ways, because there is so much work involved. If you can do it, for God's sake do it, you will get well paid for it.

RC: I suppose companies just don’t have the internal resources so much any more.

SG: Often they don't. Every company is different. We have had our best successes in the past by working with companies that are very strong in electronics, and very weak in mechanical. They are the guys who appreciate us more! There are fewer internal conflicts, and besides, we can do they job for them. You've got a Northern Telecom for example, and the design effort is separated quite clearly from the mechanical design. Industrial design and mechanical design activity are quite different. What we do here, as a small shop, is blend right through. The Industrial Design activity at Bell Northern Research would probably taper down after the end of Phase Two. There would still be a consulting sort of activity going on, and there would still be modifications, but the manufacturing drawings are produced by the mechanical design department. It would be nice if that is all we would have to do as well, as a consulting office, I think I would prefer to focus on that front-end stuff, because that is where the really unique skills of industrial design are residing, but it is hard to find somebody who can do that with the parts drawings.

RC: And that becomes some very important bread and butter, to put out those drawings.
SG: Yes. A very important step in the Phase Three process is to first of all, get those drawings done to a Rev. A level, and then prototype those drawings. There are, in the plastics business, understand that a product like that has 250,000 dollars worth of hard tooling, and therefore it makes one nervous when one takes a set of drawings, and commits that to 250 grand worth of tooling. Somebody’s neck is on the line for sure, and so the recommendation that we always make, and thank God Digital took us up on it, was that there was prototype tooling done first. And that is silicone rubber moulds, made from machined patterns, derived from the drawings. Silicone rubber moulds are very simple, and the resin is just poured into the mould. What comes out of the mould is this plastic part, made in this resin, which is an exact reflection of what your drawings have indicated.

RC: The mould preparation, this is interesting,...
SG: You deliver the drawings to these people, the specialists in this area. The drawings are then used as a basis to machine patterns. They will machine them out of acrylic, or whatever material suits, REN. In fact that pattern will be a dead nuts replica of the part, but then they go one step further, and they make moulds.

RC: And the moulds themselves are made of silicone rubber?

SG: Yes. There are two halves to the mould, a cavity and a core, just like you would do with steel. You put them together and pour the resin in.

RC: Pour more silicone rubber, or a different resin?

SG: No, a resin, a casting resin that ends up having a characteristic sort of like the plastic that you are going to use. It’s not the same though. Those parts are then used to prove out the drawings, and to prove out the assembly, because you can put all the parts in, the circuit boards in, the display, see if it works.

RC: I was interested in the process. I had a part and I used a spray metal prototype mould, and actually made a run of injection moulded parts, a few hundred out of the mould.

SG: That is one step further, or one step up from the silicone rubber mould. The cost for this product was something in the order of thirty thousand dollars for five sets of parts. There were some minor changes made to the drawings. There were some bosses added, there were some screws removed, there were changes from screws to snap-fits, various things.

RC: Those were cases of parts fitting to parts. Were there instances of drawing inaccuracies that were never intended?
SG: There were of course, but they were very minor. Fortunately, everything went quite smoothly, and everybody was delighted with the way it went.

RC: So the drawings were a very good representation of the intent.

SG: They weren't a good representation of the intent, they were the manufacturing drawings. At that point the intent is understood, at the end of Phase Two.

RC: Sure, sure. Obviously one of the important things in proving the drawings, is you know, when you get a part that is this dimension, in terms of error correction, in a robust system. I'm sure GM has all sorts of people worrying about are the dimensions on the drawing what we intended.

SG: Yes, and that process of developing the drawings has been made so much easier by CAD, because you can fit them together on the screen, and you have a very good idea that things are going to work, and you have automatic dimensioning, that removes the human error of miscalculation, misreading, or whatever. All of that stuff is automated to an extent, so the probability of success is enhanced quite a bit, I'd say.

RC: So you have that much more confidence before you go spend your quarter of a million bucks on tooling, that you are getting...

SG: Yes. The final proof is that set of prototype parts. Of course, it also gives the opportunity now to make some adjustments to make it even better. All the ideas that you have ever been able to garner, are all piled into the original set of drawings, and having then received a set of prototype parts, you put it all together, and you go shoot, there's a great opportunity to do this, and you never saw it before, because you were never able to get inside the product. The last verification you had was a solid kind of a model which proved the outside, but the inside was still a little bit up for grabs. You can visualise the inside through drafting, but once you have it there, you have prototype parts, there are some opportunities.

RC: Can you think of one or two things that sprang to mind in this particular instance.

SG: Well one thing was, going back to that cleanliness issue. The product had to withstand being washed down with this ammonia solution, and we found that on the prototype assembly, that the solution went nicely through the keys and didn't cause any failures on the keys, but liquid was accumulating inside the case, even though there were designed-in drain holes. It was dripping through unexpected places, and starting to run into the circuit boards, and so a whole series of little walls was added into the base component, so that if stuff did drip through, it was contained, and in fact the inner surface of the plastic was just tweaked slightly to create a slope, so that the stuff would drain out. It was just like when you pour a basement floor, you want to make sure it all goes down to the same drain. The same thinking was applied to the inside of that case,
and you could never have known that without having had some experience with it.

So, then having received the prototype parts, another thing that they were able to do with the prototype parts, of course, was to put some together, out them out in the field, and get some user response with these things. It was the first time that the hospital guys had a chance to ...

RC: So real components, prototype plastic housing, and put one together and make it work and test it out.

SG: Yes. Let’s see, was there anything changed there?

RC: Before you get into that, was there any kind, I’m sure that they must have had some sort of working models, probably not in user trials, like a bigger computer with the same information on it?

SG: Oh yeah. They did that, they ran PC’s. Ran the software on the PC’s.

RC: To prove they were doing the right things, capturing the information in the right ways? But that was all Digital’s, Digital and the customer.

SG: Yes, it had nothing to do with the product design. Essentially that tells the story. From that point on, it was a matter of going down to the moulder, or selecting a moulder, and going down to spend time with the moulder. Again some improvements, which the moulders saw, they brought their expertise into the picture which will always cause some refinements to the drawings.

RC: This is in terms of runners, and how you mould things,...?

SG: Yes, maybe adjusting the draft a little bit here and there, and maybe changing the depth of some of those little walls or ribs, because they might get burn-out in the tool. There is a number of things that these guys can see straight away, and no matter how good you are, you miss them when you are designing the plastic part, and working out where the gating is going to be, that sort of final stuff. Then moulding up the parts, getting the first ones off without texturing, then specifying the texturing.

RC: You get them without texture?

SG: You always do that, because this gives an opportunity to do final testing on the first-off plastic parts. If there are any changes to be made that require re-machining of a visible surface, then if you have textured it already, now you have really blown it, because you’ve got an area that must be machined, and has to be polished, and selectively textured, in an attempt to match it to everything else. You are really in trouble. So the very last step is to texture the moulds, that’s for sure. And that’s it.
Parts come off, and the Beta testing goes on, the first crop are out there functioning in a real-life situation. The final orders are taken, and big volumes are produced.

RC: And then you get design awards.

SG: Well, in this case, yes. It was a very good, very good, almost a text-book project, from that point of view, everything went well. The only thing that didn’t go well was the fact that we didn’t get any work after that.

RC: Which has nothing to do with that project.

SG: No, it’s pure economics. It’s the realities of the recession coming crashing down. It was a text-book project, I’ve never encountered anything that went so smoothly.
Appendix C

A DEFINITION OF DESIGNING

"Designing: is describing a new possibility, which is expected to allow the achievement of a preferred situation."

Introduction

A symptom of our poorly-developed theoretical understanding of designing, when compared to our better-developed practical understanding of designing, is the absence of a broadly accepted, or consensus, definition of designing. There is evidence in the literature that indicates this lack of agreement within the design community on a consensus definition of 'design' or 'designing'.

Robin Jacques (1981) comments in the preface to "Design: Science: Method":

"Design, though the object and the subject of our common interest, remains ill defined. Many writers still find it necessary to preface their work with a personal attempt at definition as a context to their own concerns. ... The difficulty of actually knowing what design is stands in the way of communication about it, and even of constructive thinking about it. Not least it affects our ability to make effective sense of such terms as design research or design method."

David Ullman (1991) indirectly provides evidence describing the specific effects that the lack of an agreed definition of design can have. In a paper on the status of design
research in the United States, where he describes the first planning meeting of the National Science Foundation's Design Theory and Methodology program, whose goals were to fund research in: (1) scientific theories of design, (2) foundations for design environments, and (3) models of the design process, he writes:

"the meeting was not very successful as there was no agreed definition of 'design' and little unity on the approach to studying it."

Further on in the paper he comments that the Design Theory and Methodology program has drifted since its inception, and great progress has not be made in the philosophical science of design. One can only speculate on the exact benefits that an agreed design definition could have provided, but one could have expected some positive effect on the program's progress.

The lack of an agreed definition continues to be an important, yet unresolved issue, as further evidenced by the fact that the very first item on a list of things to do, in a summary of discussions held by the Design in Engineering Education Division (DEED, 1992) at the 1992 annual meeting of the American Society of Engineering Education (ASEE) is:

"Produce a 'consensus' Definition of Design".

This appendix will examine existing definitions, and develop a suggested possible candidate for a consensus definition.
Existing Definitions of 'Designing': A Literature Review

As with design models, there are broadly general definitions of 'designing' or 'design', and there are self-restricting definitions. A self-restricting definition is one which is intended to be general, but in fact is not, and may limit itself to a certain design specialty, or even a type or size-range of design project within that specialty.

The following examples demonstrate self-restriction:

"A definition that contains the necessary ideas and speaks broadly of design follows.
'Engineering design is an ...'"

(Middendorf 1986)

"Designing is defined as follows:
'Engineering design is a ...'"

(Eder 1990)

The irony of attempting to speak broadly about design, yet constraining the definition to a particular design specialty, is obviously unintended by these authors. Unfortunately, it is not atypical of design activity authors from many specialties, and not just of engineering design activity authors. It is merely symptomatic of the division between various academic specialties, and also of their respective schools of knowledge. The result is that general description and study of designing is clouded by self-restricted non-general design definitions. There are only a few authors such as Alexander (1970), Gregory (1966) and Simon (1969) who have described designing in truly broad terms.
As Jacques indicated, most (about 4 out of 5) design writers begin their work by providing a short definition of design, designing, or the purpose of design. Over 30 collected definitions were selected, and are those which attempted to describe design from a broader perspective. They are in alphabetical order by author.

**Design, and/or Designing, is:**


Finding the right physical components of a physical structure.

Archer, B. (1965).

A goal-directed problem-solving activity.

Selecting the right material and shaping it to meet the needs of function and aesthetics within the limitations of the available means of production.

Design is a goal-seeking activity, in which a model or a prescription is formulated in advance of embodiment for an artefact, which is offered as an apt and original solution to a given problem.


The goal of the engineer is to utilize knowledge of the physical world for social benefit. In order to achieve this end he designs or builds devices, structures, processes and systems. The problems which he seeks to solve have many possible answers from which he must select an appropriate, and hopefully an optimum solution.

Engineering design then is the process of applying the various techniques and
scientific principles for the purpose of designing a device, a process or a system in sufficient detail to permit its physical realisation.

A design problem implies action and a final result which has physical reality, not a result which is only an idea or a report.

One characteristic of a design problem is that there is no unique solution; in fact to ask for the 'correct' answer to a design problem is to ask a meaningless question.


Decision making, in the face of uncertainty, with high penalties for error.

Engineering design is a purposeful activity directed toward the goal of fulfilling human needs, particularly those which can be met by the technological factors of our culture.

Booker. (1964).

Simulating what we want to make (or do) before we make (or do) it as many times as may be necessary to feel confident in the final result.


An activity of a special kind: the contemplation (and analysis) of a relation between two states - before and after.


Design is a fundamental, purposeful human activity. Designers are change agents within a society; their goal is to improve the human condition, in all its aspects, through physical change. Design involves a conscious effort to arrive at a state of affairs in which certain characteristics are evident.

In a sense, perhaps it does not matter how the designer works, so long as he or she produces that final description of the proposed artifact. When a client asks a designer for 'a design', that is what they want, the description. The focus of all design activities is that end-point.


Devise, subject to certain problem-solving constraints, a component, system, or process to accomplish a specified task optimally, subject to certain solution constraints.


The specification of an artifact (or change in an artifact), in sufficient detail to both construct it and to determine its performances in all dimensions of interest.


Engineering design is a process performed by humans aided by technical means through which information in the form of REQUIREMENTS is converted into information in the form of descriptions of TECHNICAL SYSTEMS, such that this technical system meets the needs of mankind.


The conditioning factor for those parts of the product which come into contact with people.


Engineering design is the use of scientific principles, technical information and imagination in the definition of a mechanical structure, machine or system to perform prespecified functions with the maximum economy and efficiency.
Relating product with situation to give satisfaction.

The antonym of accident. As a professional activity this seems to reflect what employers and users expect, i.e. a process which defines a change of state of a limited and preferred sort and the means of bringing it about under control.

The performing of a very complicated act of faith.
To initiate change in man-made things.

In Chapter 3 we looked at simple definitions of design and concluded that such a complex process defied simple description.

Matchett. (1968).
The optimum solution to the sum of the true needs of a particular set of circumstances.

A definition that contains the necessary ideas and speaks broadly of design follows. Engineering design is an iterative, decision-making activity whereby scientific and technological information is used to produce a system, device, or process which is different, in some degree, from what the designer knows to have been done before and which is meant to meet human needs.

The imaginative jump from present facts to future possibilities.


Total design is the systematic activity necessary, from the identification of the market/user need, to the selling of the successful product to satisfy that need - an activity that encompasses product, process, people and organization.


A creative activity - it involves bringing into being something new and useful that has not existed previously.

Design is the essential purpose of engineering. It begins with the recognition of a need and the conception of an idea to meet this need. It proceeds with the definition of the problem, continues through a program of directed research and development, and leads to the construction and evaluation of a prototype. It concludes with the effective multiplication and distribution of a product or system so that the original need may be met wherever it exists. J.B. Reswick, in the foreword to Asimow.


To design is to formulate a plan for the satisfaction of a human need.

In engineering it is still the process in which scientific principles and the tools of engineering - mathematics, computers, graphics, and English - are used to produce a plan which, when carried out, will satisfy a human need.


Everyone who designs devises a course of action aimed at changing existing situations into preferred ones. The intellectual activity that produces material artefacts is no different fundamentally from the one that prescribes remedies for a sick patient or the one that devises a new sales plan for a company or a social welfare policy for a state. Design, so construed, is the core of all professional training: it is the principal mark that distinguishes the professions from the sciences. p 129

Every field of engineering involves and depends on the design or synthesis process, which allows us to fulfill needs through the creation of physical and/or informational structures, including machines, software, and organizations.


Mechanical design is the refinement from abstract representations to a final physical artifact. Mechanical design problems begin with an ill-defined need and result in a piece of machinery that behaves in a certain way, a way that the designers feel meets the need. The design process is a map for how to get from the need for a specific object to the final product.
The Problem Approach

We have seen that the problem of achieving a consensus definition of designing has been recognised, and appears to be unresolved. We must look at how the problem may be approached.

It must be realised that there is no guarantee of achieving unambiguous meaning for a word like 'designing', when one must use other words to define it. There is the possibility of circularity, and recursion. However, in practice, one may judge among various definitions, and select better examples, based on issues that may be deemed important, such as logic, clarity, conciseness, precision, utility, and scope or range of application.

The problem of developing an improved definition of 'designing' was approached in two ways. The first approach was to decide on some desired objectives for a definition, and then to examine existing definitions, one by one, and phrase by phrase, or word by word, and discuss the logical implications of each phrase, and the preferences for the best choice of competing phrases which seemed directed at similar concepts or meanings. The best of the best were retained in a working definition until all existing definitions had been examined and dissected. The progress of this approach is described in detail.

The second approach was to use the Information Web modelling technique that is
described in the main body of the thesis. An information web diagram that diagrams a number of existing definitions in relation to each other, is included at the end of this appendix. The web provides an interesting way to compare similar phrases that describe a common topic, and provides a structure which makes the various important topics visible.

Objectives for the Definition

In order to choose or create a definition of 'designing', objectives for the definition were established. The chosen objectives were that the definition should be:

- Simple,
- Comprehensive,
- Precise in how it separates what is designing from what is not designing,
- Logically sound,
- Applicable to a broad range of design specialties, sizes and complexities of project,
- Representative of, and accommodating of, the essential characteristics described in existing definitions.

The objectives were chosen solely because they were deemed to be useful objectives. There does not appear to be any existing methodology for definition described in the design literature.

A Methodology for Defining 'Designing'

In order to develop a definition of designing from a comparative examination of the
existing definitions, the following methodology was chosen.

Component phrases or concepts of a definition were examined to determine if they are also found, or are more simply described by similar phrases, in other definitions. The comparisons were judged using the following guidelines:

In the case of several different descriptions of the same or very similar concepts, the simpler description of the concept is retained. Simpler is chosen to mean the use of fewer words, or stronger, more inclusive, less restrictive words.

Concept elements are tested by removing them from individual definitions. The modified definitions which result are examined to determine whether the modified definition continues to uniquely describe an activity commonly accepted as designing, or if it has lost some meaning, and can now describe some activity other than designing. This tests for simplicity. If the removed phrase does not materially affect the definition, then it is non-essential, and may be discarded in favour of simplicity. If the meaning substantially changes, then the tested concept phrase is essential, and must be kept.

When a concept is expressed in one author's definition, but is left unexpressed in another's, there are three possibilities:
- The concept in question is non-essential and can be discarded.

- The concept is essential, and its meaning has been included by implication by other phrases in the other definition, if the other definition does not directly state the concept.

- The concept is essential but has been overlooked in the definition that does not include it. The concept should be either directly included in the definition which is being developed, or the concept should be necessarily implied by other phrases in the definition being developed.

The tests for broad applicability are that the proposed definition of designing should serve to describe such extremes as:

A very short 5 minute individual design exercise, as well as

A very long 500 person 5-year project, and

A range of design specialties, such as:

- computer software design,
- graphic design,
- architecture,
- industrial design, and/or
- engineering design, for example.
The Development of a Definition

Both the resulting definition of 'designing' and the progress of its development are presented, as both are useful. The developed definition is:

Designing is: Describing a new possibility, which is expected to allow
the achievement of a preferred situation.

The intended utility of the definition is to improve our ability to describe a theoretical understanding of the practice of designing.

Describing the development process of the definition is also useful for two reasons. Firstly, it serves as a collection of supporting arguments for the validity of the presented definition, by presenting and documenting arguments in favour of using certain component concepts and phrases, as well as arguments against the use of certain concepts or phrases. Secondly, and most importantly, describing the process, or methodology that was used to produce and refine a definition of designing, is also useful because it documents a methodology, which itself may also be refined in the future, which can be used to produce a better definition, if necessary. This last consideration is made in light of the fact that while some authors in the design community have suggested that a better (consensus) definition of designing would be useful, no one appears to have taken the next step to suggest how that might be achieved.
This discussion of future refinement of both the definition and the process of developing a definition is explicit admission and recognition that the presented definition is not a rigid final result, but the present best refinement of past definitions. It is important to note that it does come from a refinement process, that does consider other definitions, and is not intended to represent only a personal point-of-view, or to be a less carefully constructed general lead-in or introduction to a book on designing.

While this written record is not an exact copy, and proceeds much more directly than did the actual mental development process of the definition, this recorded presentation shows the typical thought processes and the specific relevant arguments in support of the developed definition. The arguments were arranged for simplest presentation to the reader, and it is only because of this arrangement that the developed definition seems to be directly derived from Simon's (1969). The similarities in the definitions are a reflection of the strength of Simon's definition relative to the described objectives for a consensus definition, and the differences relative to Simon's definition point out the suggested improvements that are discussed in the text.

The process begins by selecting an existing definition, and making it the initial definition-in-progress, which can by itself be tested for simplicity, logic and breadth of application. After passing those tests, with modifications if necessary, another existing definition can be offered up for comparison, to begin the search for the essential phrases or concepts that will best combine to form the desired definition. As better words or phrases are
found, they take their place in the ever changing definition-in-progress. The definition must also be changed in response to any difficulties of logic or meaning that a new design observation may highlight. Each design definition is compared to the developing definition, until all have been considered. This process has no absolute end, as the presented definition can continue to be tested and modified through comparison with any newly encountered definition of designing, or newly suggested alternative phrasing. The form of the definition at any time is therefore only the best possible choice of words that satisfies the definition objectives at that time.

The format for the following iterative development of the definition of 'designing' is:

Discussion

Existing definition (external source).

Discussion

Designing is: (definition-in-progress).

Discussion

The Definition Development Process

Any definition can be used as a starting point, in this instance, Alexander's.

Finding the right physical components of a physical structure. (Alexander,
To begin, this definition could possibly be simplified by removing one, or both, of the 'physical' adjectives, and examining for any changes in meaning. This small change is probably not worth pursuing, as the definition is only a starting point, and may change in many more significant ways. In fact, although Jones (1970) presented this statement as a definition of design, Alexander did not make quite as broad a claim, but in context was only describing the specific problem facing him in an Indian village design project. In any case, it is temporarily retained as a starting off point, and becomes the definition-in-progress:

Designing is: Finding the right physical components of a physical structure.

Now consider:

Decision making, in the face of uncertainty, with high penalties for error.

(Asimow, 1962).

The two phrases that modify 'decision making' do not appear to separate what designing is from what it is not. Examining the last phrase, 'with high penalties for error', the question is asked, "If the penalties were lower, would the resultant activity still be
designing?" The answer; lowering the level of penalty does not change the activity from being designing to not being designing. The importance of careful designing may rise with risk, but risk is not an essential defining element of designing. Both modifying phrases may be seen as colourful, but they do not appear to add precision to the definition of designing, and will not be retained. With the inclusion of decision making in the definition-in-progress, the combined result is:

Designing is: Finding and deciding on the right physical components of a physical structure.

Consider:

Simulating what we want to make (or do) before we make (or do) it as many times as may be necessary to feel confident in the final result (Booker, in Jones, 1970)

This brings out the notion that the designing happens in advance of the making or doing. This definition also expands upon describing 'the making of a physical structure' to include 'doing activities'. As these concepts appear to add meaning to the definition, consistent with our practical understanding of designing, they will be added.

Designing is: Finding and deciding on the right physical components of
a structure (activity) before making the physical structure (doing the activity).

Consider:

The imaginative jump from present facts to future possibilities (Page, in Jones, 1970)

This definition expresses the 'structure or activity' in the developing definition as a 'future possibility'. This choice is both simpler and more broadly comprehensive, and will be retained.

Designing is: The imaginative finding and deciding on the right facts or physical components of a future possibility.

Notice that the use of the phrase 'future possibility', besides being a broader simplification of activities and physical structures, has the additional benefit of simply implying that the deciding is happening in advance of the making or doing.

A creative activity - it involves bringing into being something new and useful that has not existed previously (Reswick, in Jones, 1970)
Notice that this definition focuses the creation of something new and useful. At the same time it does not contain a direct expression of the concept of deciding on the facts of the future possibility before actually creating it. While this is perhaps assumed, recall that for the described objectives, nothing should be left to assumption. What has been added to the developing definition is the idea that the future possibility must be useful, which will be accepted for now.

Designing is: The creative or imaginative finding and deciding on the right facts or physical components of a useful future possibility.

Consider:

The optimum solution to the sum of the true needs of a particular set of circumstances (Matchett, in Jones, 1970)

This is additional support for usefulness, or satisfying the needs of a particular set of circumstances. The concept of an 'optimum solution' is introduced, as an expansion on the 'right' facts. As a simplification, a 'particular set of circumstances' can also be described as a 'situation'.

Designing is: The creative or imaginative finding and deciding on the right or optimum facts or physical components of a future possibility, to solve
the needs of a situation.

Consider:

A goal-directed problem-solving activity. (Archer, 1965).

This assumes that there is a problem, or dissatisfaction, within a particular situation, and that designing is the activity that intends to best solve or improve the situation. This fits with the developed definition. This is additional support for the concept 'a solution to needs' or 'usefulness'.

The definition can be simplified by relying on necessary implications. 'The facts or physical components' of a future possibility may be simply stated as the 'description' of the possibility. Because it is a new possibility, and not an existing one, a degree of creativity and imagination must necessarily be implied. Similarly, developing a full 'description' will necessarily involve 'finding and deciding on its component parts'. The result:

Designing is: Describing a new possibility, to solve the needs of a situation.

This definition of the activity of designing agrees very well with the following definition:
Relating product with situation to give satisfaction. (Gregory, 1966)

Gregory's definition is very concise, but like Reswick's, leaves assumed the distinction between developing the description of a product and making the product itself. 'Product' also may be more restrictive than 'possibility', depending on interpretation. The one change that will be made to the developing definition is to substitute 'satisfy' for 'solve', as it allows a broader range of the design activity, to include those instances where no single possibility is found that may be said to exactly solve the needs of a situation, but a possibility may be chosen which does provides the highest possible level of satisfaction.

Designing is: Describing a new possibility, to satisfy the needs of a situation.

And the final input definition:

Everyone who designs devises a course of action aimed at changing existing situations into preferred ones. (Simon, 1969)

Simon captures the distinction of designing prior to creation, with his use of the phrase 'devises a course of action' if the interpretation is that devising the course of action is done in advance of taking the action. As that phrase is also quite comparable to 'describing a possibility' in terms of simplicity and universality, with no greater
preference for either one, no change was made.

Note that Simon does not use the word 'new' in his definition, or any other word to indicate creativity, or originality. He does use the word 'new' in his description of a 'new sales plan' in his additional discussion of his definition, however. The new or creative requirement on the solution description is important, and will be retained, as it provides a separation of the creative activity of 'designing' from routine 'problem-solving'.

The remaining differences between the definitions lie with the phrases 'satisfying the needs of a situation' and 'changing existing situations into preferred ones'. Simon describes two different situations, the existing and the preferred. As the definition under development only refers to one, Simon's description of two situations forces an examination of the type of situation that was intended in the developing definition. The developing definition directly refers to one, but does in fact imply two situations. It directly refers to "the needs of a situation" where the situation must be an existing one, given Simon's choices. The developing definition must also imply that the new possibility will satisfy those needs, and a preferred situation will result.

The developing definition could be changed to:

Designing is: Describing a new possibility, to satisfy the needs of an
existing situation.

In practice, this is impossible.

This impossibility arising from these descriptions of various types of situations presents a logic problem, which requires the following somewhat lengthy discussion and resolution.

In any real application, design and implementation both take some finite amount of time, and as a consequence, the designed product can never satisfy the needs of an existing situation. It cannot even affect any present situation, as the designed product does not yet exist. A designed product will only exist at some time in the future, and only in some future expected situation will it have any expected satisfying effects. A designer is always working in the present, developing the description of a future product, or devised plan of action. This future product must therefore always be developed for its expected future lifetime of use in an expected future situation. A designer can not practically and strictly satisfy an existing situation.

This observation has its strongest practical implications where the design and implementation time of a product is relatively long, and/or the product is expected to have a long working life. Design difficulty is first increased by requiring the accurate prediction of a future situation, and then it is compounded by requiring even more
predictions of how a possible new product could then affect the predicted future situation.

Let us look at practical examples. For instance, if the design and implementation cycle time of a new automobile is three years, it means that if a design project is started in 1993, then designers need to accurately predict what the future market situation is expected to prefer in three years time, in 1996 and onward. For long-lived products, the designer should not design just for the single situation at the time of sale of the product, but for the product’s use over a long, and possibly changing, range of expected situations in the future. Maver (1979) uses the difficulty of designing buildings for a long range of changing times and situations as a distinguishing characteristic of architecture, although in fact, while common to architecture, the problem of designing for a long life-span can also apply in the design of other long-lived products from spacecraft to hydroelectric dams. In these cases, we should not talk of designing to satisfy the needs of existing situations, but for future expected situations.

Of course, not all design projects take a long time, or are concerned with very long-lived products. For short projects in stable situations, there is the simplifying assumption that the existing situation will not change significantly, and will closely approximate the expected future situation. To be accurate in all cases, we could change the definition to:

Designing is: Describing a new possibility, to satisfy the needs of an expected future situation.
Even at this point, we still have not fully investigated Simon’s definition, which now implies that instead of changing existing situations, we must 'change expected future situations into preferred future situations', by designing a new product, plan or course of action.

This must be tested for soundness of logic.

In testing for logic, the question arises:

How does a new possibility, or newly designed product, change one situation to another?

Upon examination, one would not expect the product to act in isolation to make the change. The mere existence of a new product cannot completely change any expected situation into any preferred one, except in the rather trivial case where the single preference to be satisfied was that a product should exist. As Archer (1965) showed in his Man-Tool-Work-Environment diagram, and Simon (1969) with his discussion of Artifact-Environment-Behaviour, the product, tool, or artifact is commonly expected to interact with certain necessary inputs from the environment, in order to provide the desired output behaviour. It is in fact a value judgement preference by the observer, desiring this output behaviour, which represents the preferred situation. The achievement of a preferred situation depends therefore not just on the isolated existence of an artifact,
or new possibility, but also on its external interactions with the environment, including
value judgements provided by an external observer, all of which combine to define the
allowed achievement of some preferred situation. It is argued that we may set aside the
requirement to change one situation into another, as it likely does not matter what
situation we have changed from, provided there is the successful achievement of a
situation which we prefer over any number of others. If we focus on the desired
outcome, the achievement of the preferred situation, the definition of designing now
becomes:

Designing is: Describing a new possibility, which is expected to allow
the achievement of a preferred situation.

All of the concepts of satisfying the needs of a future expected situation are now
embedded within the whole definition. The concept of expectation involves some sense
of future prediction, as opposed to certainty. The concept of achieving a future preferred
situation also necessarily implies the existence of some present or future predicted
situation(s) about which there is some dissatisfaction, or lack of preference. Finally,
there is also the implied expectation that none of this can happen without the existence
of the design activity. The preferred situation is only achievable through the existence
and intervention of; the activity of designing, the future existence of the described new
possibility, and the behaviour which is allowed and provided through the new
possibility's interaction with its situation.
A Summary Evaluation of the Definition

The definition can be tested for its essential concepts, by mentally removing each one in turn, and seeing the definition collapse into something that is not designing.

Without the goal of achieving a pre-described preferred situation, designing becomes an undirected artistic exploration.

Without the sense of creation that 'new' implies, then designing becomes problem resolution through the selection of existing solutions. (routine problem-resolution by catalog-shopping)

Without generating the descriptions of possible new products, or courses of action, designing is reduced to situation-analysis.

Without prior description of a possible product, subsequent creation or manufacture cannot be said to proceed according to a design, and is just exploratory working with materials.

Without evaluating the predicted performance of a possibility in a given situation, there is no expectation of achieving the preferred situation. The result could be
a described product and a described preferred situation, with no apparent or implied connection between them.

Conclusions

A definition of designing was developed and refined in a process that utilised a collected base of existing definitions. The developed definition:

Designing is: Describing a new possibility, which is expected to allow the achievement of a preferred situation.

From this exploration, the defining concepts of 'designing' are considered to be:

Designing involves a description of a future product or intended action, possibly including simulated testing, in advance of the creation and testing of the actual product or action.

Designing requires novelty, originality, or creativity of solution, to distinguish it from problem-solving.

The purpose of designing is the expected change of future predicted situations into
preferred situations. This involves uncertainty in the accurate prediction of both the expected future situation and the design activity's effect in changing it into a preferred situation. An aim of the design activity is to make more accurate predictions to reduce this uncertainty.

The newly designed product does not represent the preferred situation by itself, but usually works with certain expected inputs from its environment to produce or allow outputs which constitute the preferred situation. This may help distinguish designing from artistic activities, in which the observer's attention is typically focused entirely on the work of art itself, and not on its affect in a context, in how it functions, or what preferred situation it helps achieve.
A Complex Definition of Designing

Simplicity was considered to be a useful objective for a definition of designing. Without the emphasis on simplicity, the previously developed definition could appear as the following long version:

"Designing: is composed of many activities such as analyzing, synthesising, evaluating, testing, optimising, simulating, deciding, and creating, performed in the designer's mental domain, the physical representational domains of drawings or models, and in other domains as necessary, in order to devise, formulate and/or ultimately describe, in those domains, in the present, a possible new or original plan, course of action, or artifact, which, when eventually carried out, manufactured, or produced in the future, in its actual intended form, and placed in its intended context, with its intended inputs, is expected or predicted to provide certain outputs, which when taken altogether; the plan, course of action or artifact; its context; and its input/output behaviour; will be judged by an observer to have satisfied a want or need or to otherwise constitute a preferred situation."
END
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FIN