AD-A244 714

ARO 28409.1-MS

2

CONCURRENT ENGINEERING FOR COMPOSITES

FINAL REPORT

VISTASP M. KARBHARI*
DICK J. WILKINS*
JOHN M. HENSHAW**

DTIC
ELECTE
JAN 0 9 1992
S B D

OCTOBER 1991

U. S. ARMY RESEARCH OFFICE

GRANT NUMBER: DAAL03-91-G-0004

* CENTER FOR COMPOSITE MATERIALS
UNIVERSITY OF DELAWARE
NEWARK, DE 19716

** DEPARTMENT OF MECHANICAL ENGINEERING
UNIVERSITY OF TULSA
TULSA, OK 74104

92-00648

APPROVED FOR PUBLIC RELEASE;
DISTRIBUTION UNLIMITED

92 1 8 042

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
October 1991

3. REPORT TYPE AND DATES COVERED
FINAL REPORT

4. TITLE AND SUBTITLE
Concurrent Engineering for Composites

5. FUNDING NUMBERS
DAAL03-91-G-0004

6. AUTHOR(S)
Dick J. Wilkins
Vistasp M. Karbhari
John M. Henshaw

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Center for Composite Materials, University of Delaware,
Newark, DE 19716

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P. O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARO 28409.1-MS

11. SUPPLEMENTARY NOTES
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The Total Quality Design (TQD) approach serves as a facilitation tool for the coupled decision making necessary for composites. The approach serves as a means of enabling the concurrent engineering of composites through the use of a composites design methodology, as well as the Composites Manufacturing and Design Guide (CMDG). This serves as a decision support system, enabling the design team to not only obtain pertinent information in the shortest possible time, but also serves through its discrimination stacks as a means of rejecting concepts that are not feasible with the customers needs and wants. This serves to reduce conflict. Actual case studies are described, and the methodology is further coupled with the TAGUCHI method, to enable efficient quality control in the RTM process. The entire methodology and set of tools is structured so as to enable the design team to conquer barriers of communication, and work in an efficient manner for the successful realization of the design cycle. The approach and tools present a concurrent engineering approach to the application of the latest decision making management techniques to the product realization process for composites.

14. SUBJECT TERMS
Quality, Product realization process, deselection, discrimination, design, manufacturing, composites

15. NUMBER OF PAGES
180

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std Z39-18
298-102

Accession For
NTIS GRA&I ☑
DTIC TAB ☐
Unannounced ☐
Justification

By
Distribution/
Availability Codes
Dist | Avail and/or Special
A-1

THE VIEWS, OPINIONS, AND/OR FINDINGS CONTAINED IN THIS REPORT ARE THOSE OF THE AUTHORS AND SHOULD NOT BE CONSTRUED AS AN OFFICIAL DEPARTMENT OF THE ARMY POSITION, POLICY, OR DECISION, UNLESS SO DESIGNATED BY OTHER DOCUMENTATION.

TABLE OF CONTENTS

LIST OF APPENDICES

1. INTRODUCTION

During the last decade, the composites industry has faced increasing competition on a world wide basis. This has led to an increasing emphasis on the development of newer and improved materials and processes. As a result there is an increasing push from management to speed up the design of products and reduce the time to market. The intense competition prevalent has even been described as akin to countries being in a "product war" [Cooper, 1990]. Stimulated by this increased competition, newer technologies and changing markets, industries are responding to the competitive challenges by re-thinking their approach to product development and manufacturing, and are increasingly adopting Japanese and other tools and methods of management and quality control [Edmondson and Wheelwright, 1989]. Strategic planning has assumed a position of great importance with choices determining key success factors, dictating program continuation and shaping expectations for growth. Although composites have been used for aerospace applications for more than three decades, they have yet to achieve their full potential as materials of choice for the automotive and consumer industry. Nurtured by aerospace applications that initially emphasized high performance with little regard to cost, composites usage has increased in other areas, yet is hampered by process and fabrication economics and manufacturability issues ("we can design but can you build economically," syndrome). The chasm between design and manufacturing has often caused the material system that is a designers dream to be a manufacturers nightmare. The "data management" or communications gap between design and management has been pinpointed by many as the most difficult of chasms to be bridged in increasing the effectiveness of the product realization process [Puttre, 1991].

The tailorability of composites for specific applications has been one of its greatest attractions, and simultaneously one of its most perplexing challenges. The wide choice of materials combinations, processing methods and shapes possible, present bewildering problems of selection. In the isotropic world of traditional materials it was possible to use tables, charts and simple formulae to check the validity of a concept, thereby relegating the need for specialists to the final stages before prototyping. This is not possible in composites, where specialists in different disciplines are needed almost routinely even at the stages of concept generation. The plethora of choices available is often a designers nightmare. The cost of investigating each of the possible alternatives is very high. Added to this is the fact that decision makers often do not have sufficient expertise in all the functional disciplines needed for them to make a correct choice from the large set of alternatives. The economics related with the traditional iterative norm of product development makes it necessary to promote an integrated approach that enables a more direct form of development.

In the current competitive environment, composites have to compete with mature materials such as aluminum, without the luxury of a knowledge base about life-cycle behaviour. Thus, critical decisions often have to be made when the available knowledge is the least, thus indicating a critical need for the development of tools and techniques that would allow fast strategic decision making based on minimization of risk of failure of the product realization process (PRP). One of the most important steps in the design process is the selection of appropriate materials and fabrication processes. As has been noted before [Henshaw, 1989; Wilkins and Karbhari, 1991], the three aspects of materials, configuration, and process selection are highly coupled in composites (Figure 1).

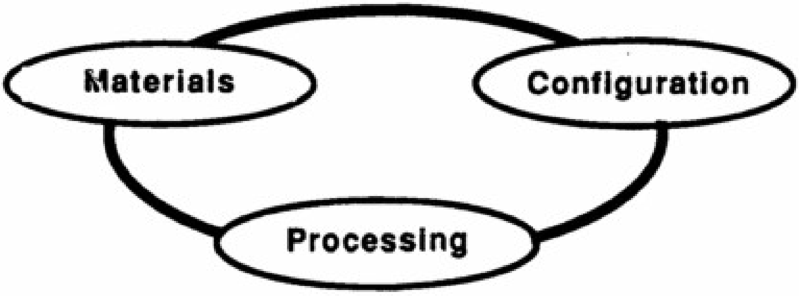


Figure 1: The coupling of decisions in composites

The composites community is well aware of the highly coupled nature of composites, as is apparent from the conclusions of an industrial survey stating that the ability to "interact" effectively with design and manufacturing engineers was the most important competency required of the "composites specialist" [Lange, 1986]. The concept of linking the attributes of performance, properties, microstructure and processing has recently been developed as an extension to the notion of the necessity of recognizing design interactions [Karbhari et al., 1991]. This allows for representation of customer wants through the attributes of performance required of the system/product. It is essential that the data representing the interdependence of the coupled aspects as shown in an example schematic in Figure 2 be made available to the design team so as to ensure that a critical interdependence is not overlooked.

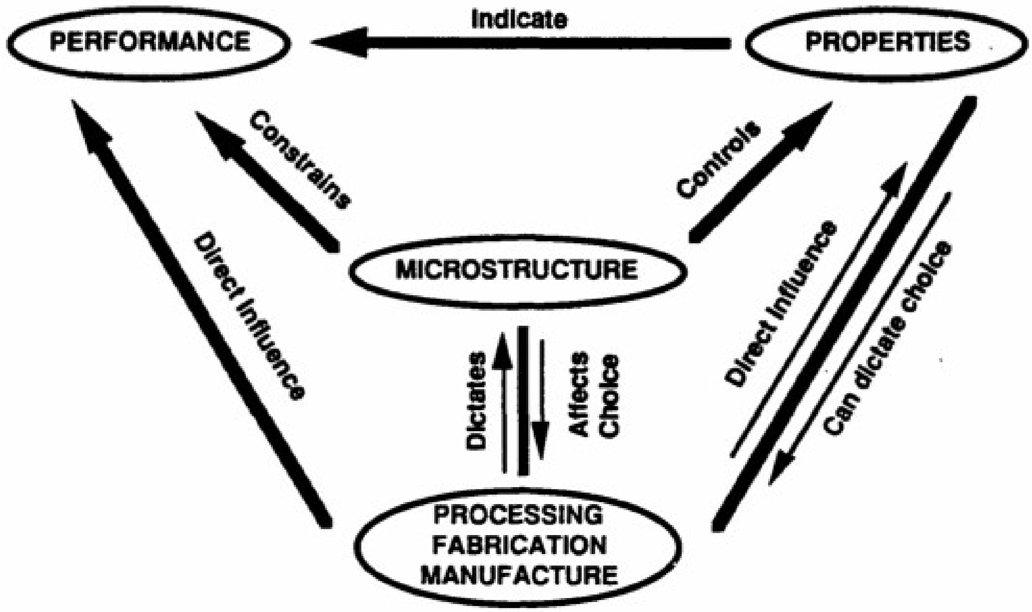


Figure 2: Design interactions and influences

The problem however, is one of data management, as related to making available sufficient information to the design team, in an appropriate fashion. Not only must this data be available, but it must be presented in a format suitable for direct application to the stages of concept generation and concept selection, thus serving as a tool for the successful execution of the PRP.

It is necessary for fast strategic decision making that the problem of selection be reduced to its main elements through the deselection (or rejection through comparison) of concepts ill-suited to the specific requirements under consideration. The process of deselection (or screening) assists the decision making team (or individual) by reducing the number of viable concepts that would then undergo a detailed analysis for suitability. This allows a rapid movement through the list of alternatives reducing the number of final concepts to only a few. The ultimate purpose is to quickly focus on the most viable and attractive alternatives. In this paper, we discuss the stages involved in composites product design process whilst emphasizing the development of an electronic environment for a decision support tool to aid the design team towards the successful attainment of this goal. The ultimate goal is the development of a concurrent engineering methodology and tools that aid the product development team in viewing and analyzing an evolving design at varying levels of routine and innovative perception, and from multiple viewpoints characterizing the integration of the different disciplines necessary for the successful implementation of the PRP.

2. DESIGN AND THE DESIGN PROCESS

As engineers, we have traditionally thought of design as an activity involved with the actual construction of an artifact, rather than with the management of the system leading to and including its construction. In fact to many engineers the term design merely reflects the mapping of system specifications into its physical realization [Katz, 1985]. Although the design process can be globally represented as the mapping of functional space to design space, it must be kept in mind that the mapping may not be unidirectional, but cyclic (Figure 3).

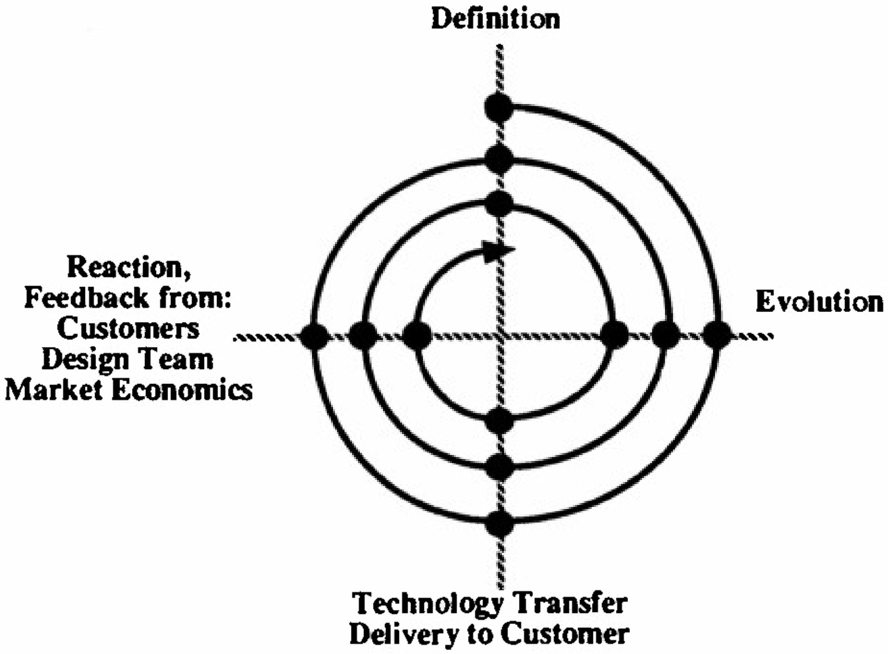


Figure 3: A schematic of the spiral design process

Waldron described the cyclic process as one in which "the designers have an idea of where to start and where to finish, but it may not be easy for them to get there without many intermediate subprocesses" [Waldron, 1990]. The process can then be conceptualized as a number of stages in which the design team interprets specifications to generate sub-functions and goals, in the attainment of which further specifications are generated in a cyclic manner, resulting in the final production of an artifact. A representative model to describe such activity was proposed by Waldron et. al [Waldron and Waldron, 1989]. In line with this, Woodbury proposed that the core for the design process was a search which characterized design "as a path planning problem through a space of possibilities" [Woodbury, 1991].

In reality, the design problem is a search that must satisfy multiple constraints and criteria. For composites, the constraints are not merely those prescribed by the design profile (or list of specifications), but also those arising from the close interaction between materials, configuration, and processes. Composites design then is not just the design of an artifact or structure, but essentially the design of the material of which the artifact is to be fabricated, and the design of the fabrication process, in addition to that of the structure itself. It is clear that this represents a new view of the terms "concurrent design" [NAE, 1991] and "concurrent engineering" [Winner et al., 1988] in that the actual process is to some degree representative of these methodologies, even in its most primitive form. For the efficient fabrication of a composite artifact, both these terms are synonymous with the design process itself.

A recent study on improving engineering design defined concurrent design as that practise of engineering design that combines the concerns of functional product and process design, production, field service, recycling, and disposal into one integrated procedure [NAE, 1991]. The development of composites is a complex process and requires the simultaneous consideration of various parameters such as component geometry, production volume, reinforcement and matrix types and relative volumes, tooling requirements and process and market economics. An illuminating example of this is in liquid molding where, in addition to the design of the material from the structural viewpoint, it has to be designed from the resin infusion aspect as well. The preform is usually designed from a structural point of view, exemplifying its use as the skeleton for the final part. Often ease of manufacture will even be considered part of the design profile for the preform. However, it is often forgotten that the same preform must also be designed from the view of infusion. The same anisotropy that comes from the use of unidirectional and specialty fabrics in order to fulfill strength and stiffness criteria can create directional flow, causing the preform to wet out primarily in one direction, leaving dry spots in the other. Related studies highlighting the use of the methodology described in this report are listed in a later section. One of these describes the use of TAGUCHI methods for the efficient determination of the critical parameters for the successful use of an immature composites manufacturing process (in this case, the RTM process) after its selection as the most applicable using the Composites Manufacturing and Design Guide (CMDG). This illuminates the use of the tools developed under the current grant and brings to the fore the crying need for the further development of concurrent design tools for composites, which would enable the design team to cover all aspects of the design problem effectively.

With the increase in complexity of streams of concurrent processes, there is an increased probability of losing control of the key characteristics necessary to add value, hold down costs and meet customer expectations. The myriad choices available make it imperative that the functions of economics, design, and manufacturing be integrated during the development process. Increasingly the composites community is becoming aware of the need for adopting the principles of quality - simplicity, elimination of waste, doing it right the first time, short cycle responses, improved robustness of products, adherence to commitments and a regard for the environmental consequences of developing composites. All this makes it imperative for the composites designer to have ready access to tools that would enable him/her to make efficient choices in the shortest possible time. One such family of tools is that related to knowledge based systems. A decision support system (DSS) is one such representation that couples information bases with a variety of problem processors intended to support decision makers.

From an artificial intelligence perspective, design can then be thought of as the search for the solution of a problem defined in global terms, but largely undefined in terms of specifics, that proceeds in an evolutionary manner from conceptualization to eventual physical implementation. The process is seen to include several levels of abstraction before a physical realization is attained. The design cycle, irrespective of its procedure, has at its heart, the goal of infusion of knowledge of downstream activities into the design process so that designs can be created rapidly and correctly. It is our hypothesis that this process can be considered in terms of five subprocesses:

1) conceptualization and preparation of a demand profile;
2) concept generation
3) pin-pointing critical technologies or attributes
   necessary for successful implementation of the PRP;
4) benchmarking and concept selection; and,
5) evaluation - the GO/NO-GO review.

The first two stages can collectively be identified as belonging to the design formulation stage, the next two with design synthesis, and the final stage as that of design evaluation. It is fourth stage that is seen as being of critical importance in competing on a world-wide basis with the "best-of-the-best". Typically design itself can be classified into routine, innovative, and creative [Brown and Chandrasekaran, 1985]. Routine design can grossly be defined as a refinement process and has been viewed as "design-prototype-instance refinement" [Gero, 1990]. In this form previous prototypes are retrieved and refined for new applications. This can be done through comparison of existing attributes with the demand profile, and making appropriate changes. In innovative design, the designer refines pre-existing designs through the use of new information and techniques. The prototype is basically used as a preliminary mask for completely new attributes. It is, however, only in creative design that new variables are introduced into the design prototype. Even though the prototype forms a disjoint set from the original, it is rare that a completely new artifact would be created. Thus it may be noticed that the design process typically evolves from the comparison and adaptation of pre-existing designs.

For an efficient process in a highly coupled environment, such as with composites, it would seem that there would be great value in having heuristics of previous designs at hand. This would enable the design team to view previous attributes and compare materials, processes, and configurations, for the best fit based on the current demand profile. One such family of tools is that related to knowledge based systems.

3. THE COUPLED ENVIRONMENT FOR COMPOSITES

The tailorability of composites for specific applications has been one of their greatest attractions and simultaneously one of their most perplexing challenges. The wide choice of possible materials combinations, processing methods and shapes presents bewildering problems of optimum selection. It is possible not only to achieve the same physical characteristics using different material system combinations, but also to arrive at them using a variety of materials transformation pathways (a schematic of a generic materials transformation process is shown in Figure 4). Obviously, one of the many routes is the optimum, the others lacking in attributes ranging from cost and durability to reliability and maintainability. Within the paradigm of traditional isotropic materials, it is possible to use tables, charts and simple formulae to check the validity of a concept, i.e., to exploit generations of successful reduction-to-practice, thereby relegating the need for specialists to the final stages before prototyping.

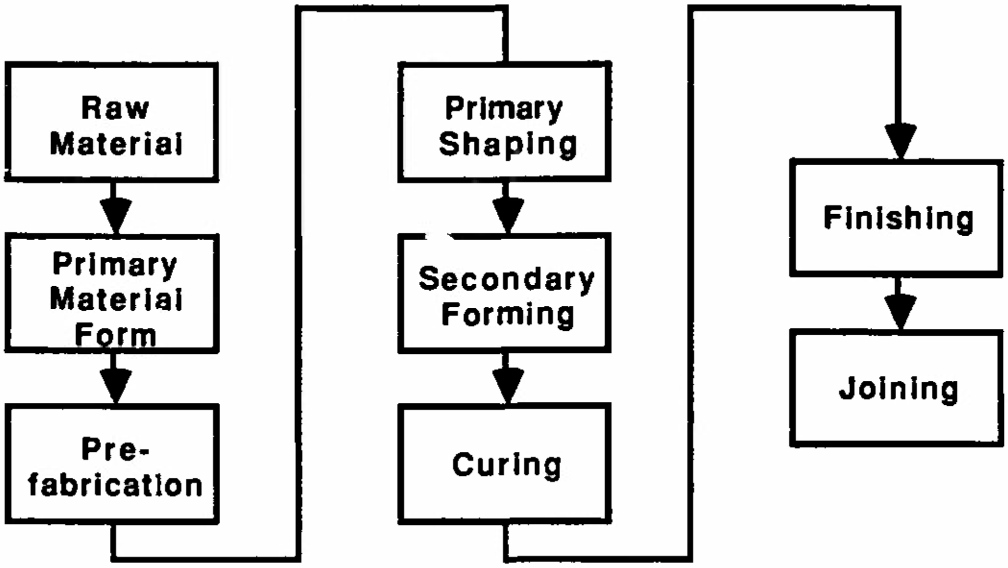


Figure 4: A generic materials transformation process

This is not possible or desirable in composites, where specialists in different disciplines are needed almost routinely even at the stages of concept generation and where very few aspects of product development have been reduced to practice. Similarly, it is possible to use vast resources of information and knowledge for furthering a mature technology, whereas this base is non-existent for an emerging critical technology. The successful introduction and acceptance of such a technology, especially in light of the immense demands placed on critical technologies, thus depends not only on a paradigm shift (from the pre-existing technology), but also on ensuring that the early decisions are correct.

Recently, a case was made to show that concurrent engineering was the ideal tool for composites product development, stressing that if it were not established in other fields, it would have been invented for composites out of necessity [Wilkins and Karbhari, 1991]. Other technologies have attempted to improve on the basic sequential (evolutionary) product development approach. However, with composites it is seldom possible to use a functionally separable decision-making process during the selection of materials, processes and configuration. Every decision made during the product development process is intricately related to the set of three interacting decision areas of materials, configuration, and processes. Satisfying the three together requires creation of a knowledge base that is capable of defining predictive relationships linking the constituents (reinforcement, matrix, filler etc.), the structural and microstructural details, and the performance attributes required from the product. The application of sequential design methods of BUILD-TEST-FIX, traditionally used for materials and product development, is both impractical and undesirable for composites. The functional connection of properties, microstructure and processing (as they reflect the integration of materials science, design and manufacturing technology) to the attributes of performance (which embody the customer wants) has recently been more fully explored [Ramkumar, 1989] in an effort to recognize critical design interactions and thus facilitate more responsive representation of customer wants through the measurable attributes of performance required of the system/product.

Our ability to efficiently and competitively manufacture composites depends not only on embracing new management techniques, but also on developing a unifying concept of materials-by-design, wherein computer modeling is combined with theory, experiments and heuristics.

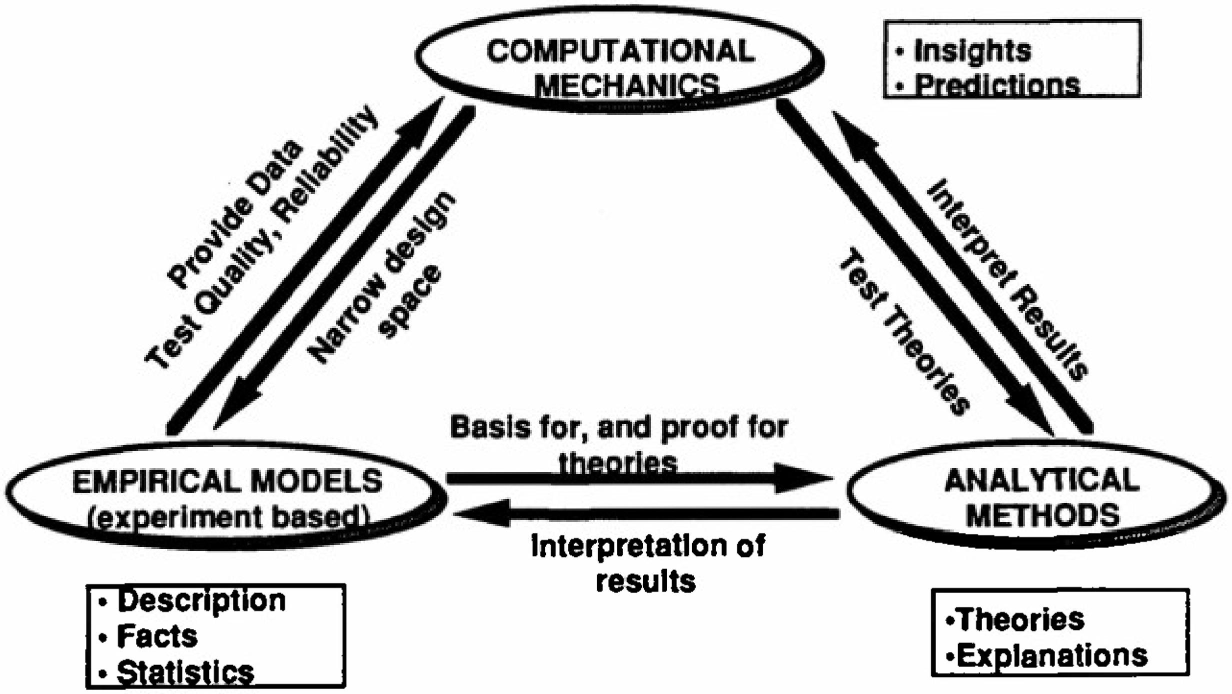


Figure 5: The complimentary use of computation, analysis and experiments

In the past, practical remedial actions in the composites test-fix loop have primarily been adapted from the metals paradigm and are often ill-suited to the task. While there remains a need to improve the traditional sequential build-test-fix design methodology for product development, emphasis must shift away from developing remedial actions and towards improving conceptual planning which can enhance responsiveness and realism at earlier stages in the process. Taken to the extreme, prior proper planning should eliminate the need for remedial measures. In any technology, the decisions made early in the product conception stage have deep implications for the subsequent stages in the development cycle. Insofar as the successful development of composites (and the associated structures) are concerned, the facilitation of the efficient selection of aspects from each of the three areas of constituent materials, configuration, and processing takes on an added dimension of importance as decisions related to these are locked into very early in the product design process. The motivation for tools to aid in facilitating the decision-making process is primarily one of economic leveraging, as seen in Figure 6.

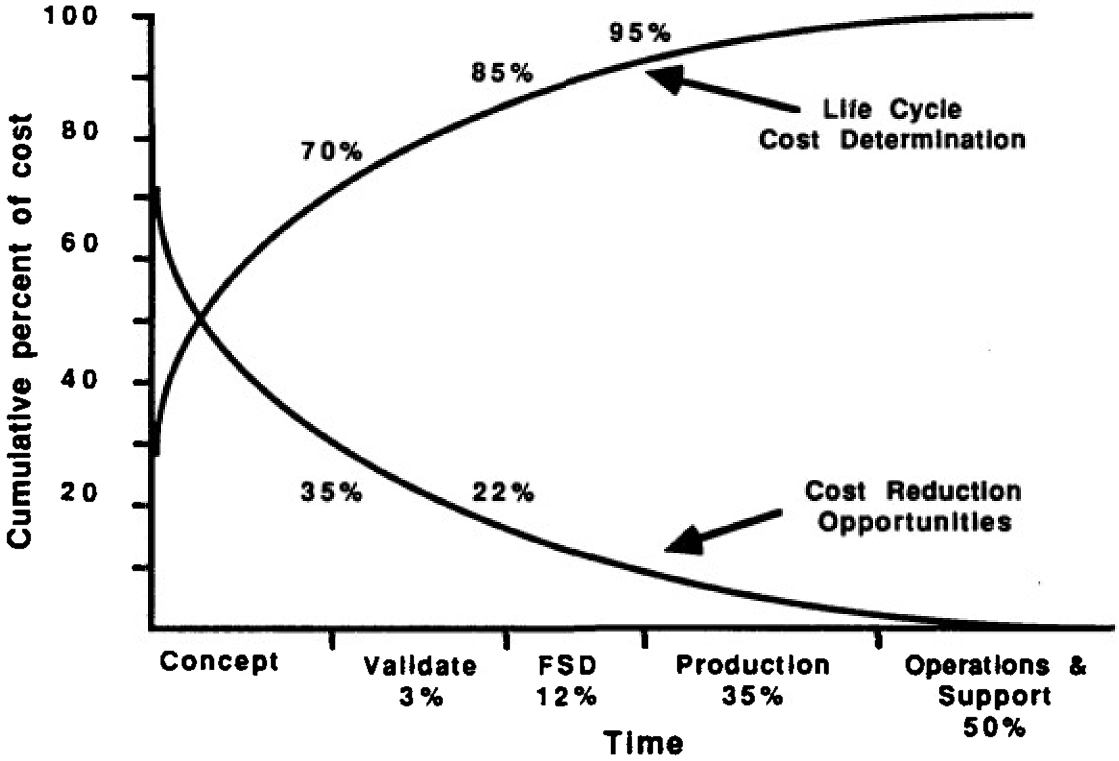


Figure 6: Opportunities in early design (after Ashton, 1991)

As is apparent from the figure, the opportunities for development–process–related cost reductions decrease as the design moves along the product realization process (PRP) time–line. Up to 70% of the total life-cycle costs are normally committed at the end of the conceptualization (or preliminary design review) stage. Due to exigencies of economy associated with product development of advanced materials, such as high initial scrap rates, high material costs and limited reworkability, early decisions are critical and have a major impact on further development. The memory of the high cost of past materials selection errors in the prototyping of composite products has often proved to be a deterrent to their conceptual selection in new programs, especially when in competition with a familiar metals paradigm which trades off potential customer satisfaction for lower risk. This situation commonly occurs with emergent technologies in fields where the customer-perception derived market forces have remained relatively constant (leading to conservativism) and in which current product paradigms must be displaced to gain market share. In all such cases it is essential that activities critical to the success of the PRP not be omitted during the product development cycle. Recent studies have shown that a minimum number of specified product design management activities must be performed in order to achieve a high success rate with new products or technologies [Cooper and Kleinschmidt, 1986; Hise et al., 1989]. Obviously, the greater the number of these activities conducted, the higher the probability of success.

The focus of this report is not primarily the development of a new design methodology for composites, but on facilitating the total design process, and with that in mind, we shall discuss a group of ideas that encourage robust early decision making by systematizing the intelligent consideration of all phases of product development.

4. A FACILITATION PROCESS

4.1 THE NEED:

American industry, faced with increasing global competitiveness, is being forced to pay much more attention to the issues of high cost and product robustness, and to the long lead times associated with product development. Stimulated by this increased competition, and by opportunities presented by newer technologies and changing markets, industries are responding to the competitive challenges by rethinking their approach to product development and manufacturing. Methods of management and quality control popularized by successes in Japan, are being adopted at an increasing rate in the United States. Strategic planning has assumed a position of great importance with a potential to determine key success factors, dictate program continuation and shape expectations for growth. In spite of its huge industrial base and R&D efforts, "the United States has earned the reputation of being the nation of the quick fix" [Renner, 1991], characterized by impatience in implementing programs, and a lack of connection with the faster–emerging technologies and management techniques of Europe and Japan.

In a recent article Kim Clark stresses the inherent paradox in technology development: "Technology has never been more important; yet building a competitive advantage by means of technology alone has never been more difficult" [Clark, 1989]. The increasing industrialization related to advanced materials in Europe and Asia has brought about competition on a worldwide basis. In its wake, a greater emphasis has been placed on a company's ability to introduce new products successfully. In the fast–changing socio-politico-economic markets of today, product development has to be approached not merely as a marketing or technological problem, but rather as one involving creativity, innovation and interactive problem solving. The business climate of the near future will in all probability place an increased emphasis on a company's ability to establish a reputation or a market niche for new products quickly. There are, however, few conceptual strategies or methodologies to aid in formulating the strategy for new product development [Cooper, 1987], let alone in developing new technologies. This has led to a renewed interest in strategies for successful product development [Cooper, 1987, 1990; Gomory, 1989; Gupta and Wilemon, 1990; Hollins and Pugh, 1990] and the formulation of new management techniques that would guarantee the success of the product realization process (PRP). For successful commercialization of new products and technologies, the functions of research and development (R&D) and manufacturing must work more closely together. Although this may seem simple enough, one need only consider the diversity in the scope and charter of the two disciplines to realize that achieving this synergism will require a tremendous uphill battle.

The traditional engineering design environment encourages free thinking, creativity, and innovation [Turtle, 1990] yet the current management system preordains the separation of the designer from the actual PRP as run by technologists and increasingly non-technical management. The manufacturing environment, in contrast, places greater emphasis on documentation, methodical planning, and the impact of design detail interrelationships on firm, immediate goals dictated by the beckoning market. Within the process of manufacturing itself, there is an acute need for coordination between designers and those responsible for actual production to help sort out these interactions. Although all involved in the PRP agree that there is a critical need for design that anticipates production, there is little or no agreement on the mix of design-manufacturing in the management of the PRP, or on how to resolve the inherent differences and trade-offs connected therein [Ettlie, 1988]. This is fast becoming of increasing concern, since without the synthesis of the different functions necessary for successful technology development (including those of management), it will not be possible to integrate the technology development phase with the sales and marketing phases. Top management has often been perplexed by "their inability to implement improved manufacturing techniques and the philosophy of continuous improvement," [Ashton et al., 1990] inspite of the apparent understanding of the need for change, as well as the commitment of the line managers to the new paradigm. Describing the emerging theory of manufacturing, Peter Drucker goes as far as to suggest that in the coming years manufacturing will have to be embedded in the economic process of business [Drucker, 1990]. Thus every decision in an industrial environment, whether related to R&D, design, or production would have to be treated as a business decision. It is in the integration of all these disciplines that we falter.

Faced with increasing global competitiveness and increasing quality of traditional materials, the composites and advanced materials industry is challenged by such issues as high cost, product robustness and long lead times associated with product development.

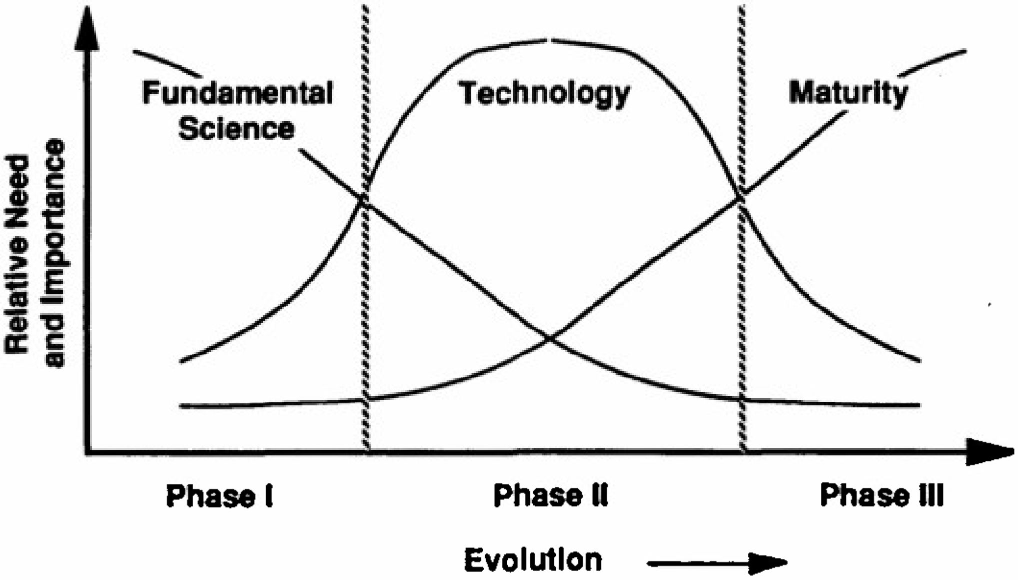


Figure 7: The phases of technology evolution

For perspective, the technology associated with composites can still be positioned in the first two stages of technology evolution as depicted in Figure 7, since technical and commercial uncertainties are limiting their advances in terms of cost and reliability. It is in the second stage that the transition from the laboratory model and prototype is made to commercial application, and this is perhaps the area that needs immediate attention. Scientific theory has to be converted to application, and research activities have to be aimed towards the development of tools and techniques to assure successful commercial development. This does not mean that fundamental issues are to be abandoned, but rather that there exists an increasing need to provide economic value by merging past and current scientific accomplishments into technological advances. Rapid changes in raw material quality as well as in composites processing technologies are causing accelerations in product life cycles. As with any other product, the life cycle can be divided into four phases: introduction, growth, maturity and decline (Figure 8[a]).

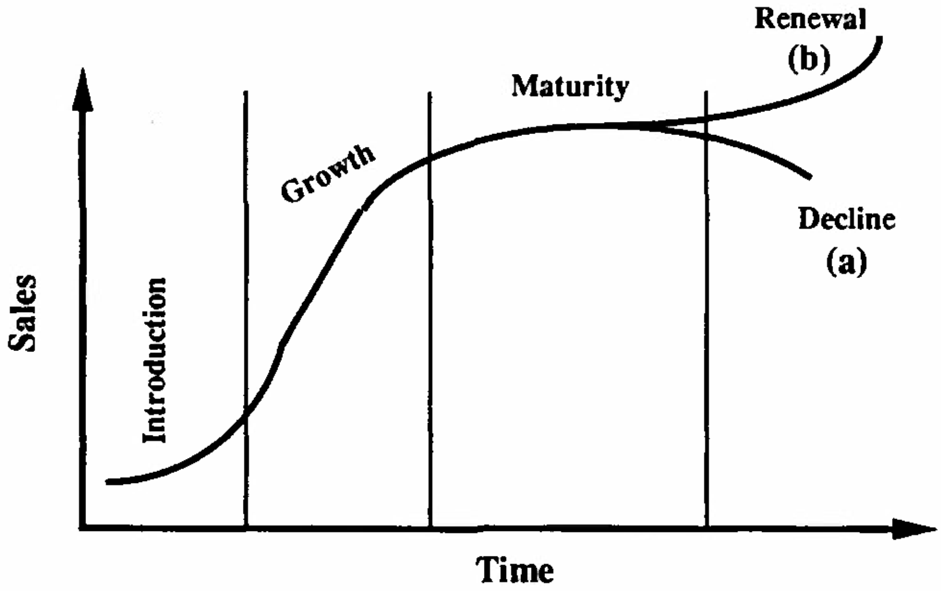


Figure 8: The product–life–cycle curve showing (a) decline and, (b) renewal

Due to the growing need for stronger, lighter and more efficient advanced materials with multi-functional aspects, the related technologies are in the ironic situation of having reached (or being close to) maturity, even though the science base is not well understood. In many cases this has caused an early decline due to problems related to reliability or cost, whereas in others the intense need has led to a renewal (Figure 8[b]) through breakthroughs. Filament winding is one such technology that has benefitted by the introduction of new and improved heating techniques (such as IR and laser assistance) as well as through developments in robotics and controls. Whereas the strategies for tackling the declining phase of a consumer product are fairly clear, it is not well understood as to what should be done in terms of a process or technology. Typically, mere substitution is not the answer. Considerable success has, however, been achieved through the use of new methodologies that stress concurrency and integration of the different stages in the PRP such as design and manufacturing [Martin, 1988]. Although much touted, these methodologies have not been applied sufficiently to advanced or critical technologies such as composites mainly due to the fine line between research, development, and actual production. There is obviously a critical need for techniques and methodologies that will aid in the seamless integration of research, product design, manufacturing, marketing, and service. The current Total Quality Management (TQM) revolution presents a number of opportunities towards this end, but the key to implementing this revolution remains in developing a facilitation process that is simple yet capable of addressing the diverse needs of the various disciplines that must work together in concurrent fashion for successful product development. In the following sub-section we describe one such facilitation process, the Total Quality Design (TQD) approach, using composites product development as an example of its application to an emerging advanced technology.

4.2 TOTAL QUALITY DESIGN:

The basic concept of concurrent engineering as a mode of integrating product and process design has been gaining favor in the last few years. Combined with the renewed emphasis on customer satisfaction stressed by the Quality Functional Deployment (QFD) methodology [Hauser and Clausing, 1988; Sullivan, 1986], concurrent engineering is popularly touted as the cure for the ailments of American industry. However, it must be remembered that such methodologies are not magical processes that will solve all problems instantly, nor is the application of these served through the addition of a "quality engineer" or a "concurrent engineering specialist" on a product development team. Product decisions include those involving materials selection and configuration, as well as decisions on major components of the design and the basics of systems integration. Production decisions can often begin with the economic decision to make or buy at the system detail level. At this stage a production plan is drawn out that includes details of facilities and equipment required, policies for tooling, and plans for producibility. Decisions on lot sizes and schedules which are directly affected by market economics are basically units of management control. In older industries, or in technologies that have reached maturity, competition is usually on the basis of production efficiency. In newer and developing technologies, competition is based not only on production efficiency and economic criteria, but also on product innovation, criticality of advanced technology, timeliness of product market launch, market pull, and quality.

There is a need to identify the main elements critical to the success of such a PRP, as well as to develop a facilitation process to improve product and technology development. The proposed approach is referred to as Total Quality Design (TQD) because (1) it emphasizes facilitating the product realization process in terms of design management and (2) it is a hybrid derivative of TQM techniques and Pugh selection matrix concepts [Pugh,.1990]—the latter in its application as a spread-sheet-based decision productivity tool. TQD has been developed to make the same principles of resource leveraging and decision robustness used in methodologies such as Quality Function Deployment, which is primarily useful in strategic planning, palatable to project–oriented technical decision makers. TQD is a team–oriented framework for integrating, prioritizing, and abstracting the essential, most relevant information needed by an engineering project leader or design team in order to come to a timely decision as to which, if any, is the best course of action given the informational and resource constraints available. The approach is based in a concurrent engineering environment and pays special attention to the importance of controlling costs and time associated with uncertainty and risk. The actual process is made up of five elements or stages: definition, requirements, benchmarking, concepts, and review. Each of these stages except the last, have two components, each of which has a dual nature: a "creative" and a "disciplined" side. Each component will be described in detail in the following section. Figure 9 depicts the fundamental components of TQD, along with some of the characteristics of each stage. It is stressed that the depiction in a "concurrent" manner should not be taken to imply the order or duration of each stage or component. The design cycle, irrespective of its procedure, has at its heart the goal of infusing awareness of downstream production activities into the upstream design process so that robust designs can be created rapidly. It is our hypothesis that this process can be considered in terms of five sub–processes, which roughly match the five stages of the TQD process mentioned earlier:

1) conceptualization and preparation of a demand profile;
2) concept generation and benchmarking;
3) pinpointing critical technologies or attributes necessary for successful implementation of the PRP;
4) benchmarking for concept selection; and,
5) evaluation - the GO/NO-GO review.

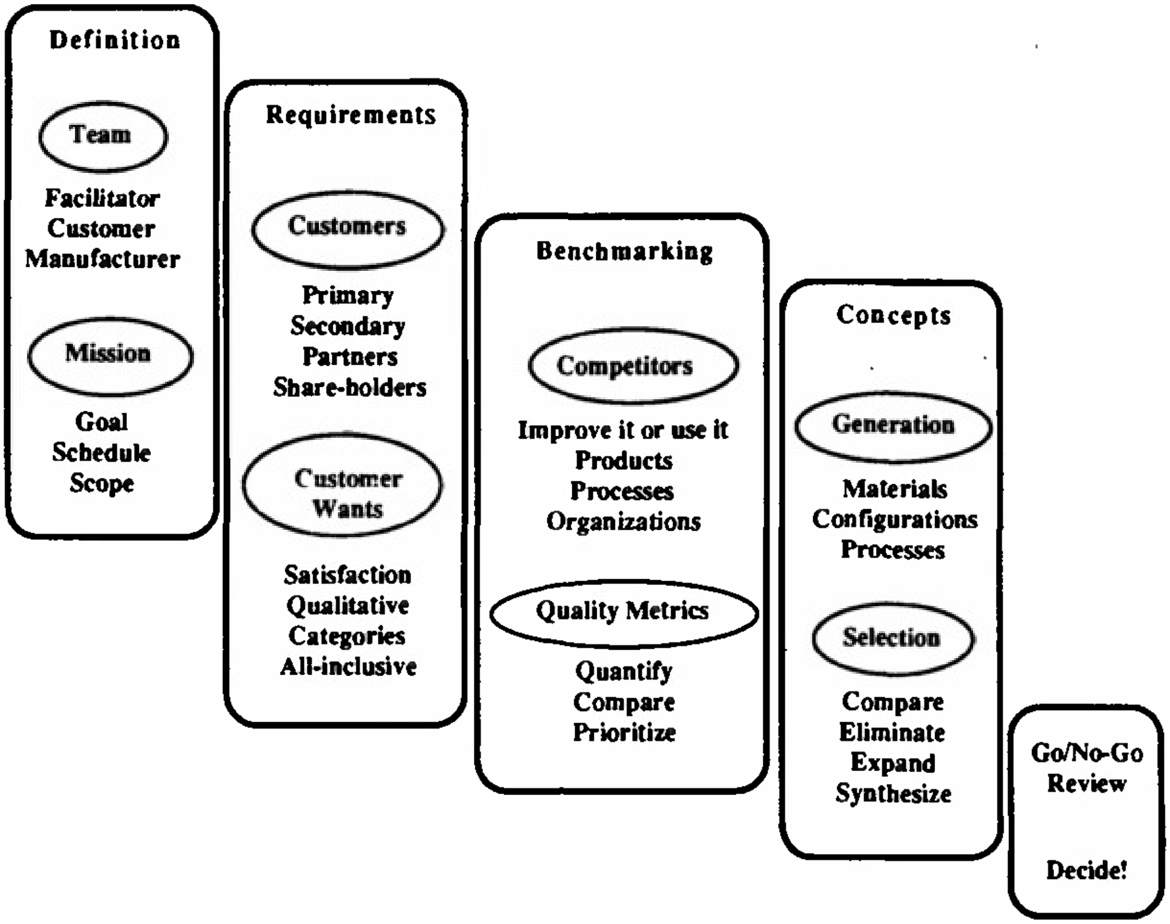


Figure 9: The elements of the TQD process

The first two stages can collectively be identified as belonging to the design formulation stage, the next two to design synthesis, and the final stage to design evaluation. A simplistic model of the design process is depicted schematically in Figure 10. However, this errs in its linear nature which suggests that no iterations are needed and undermines the importance of determining customer wants, and of synthesizing the final solution based on the evolution and deselection of a large number of potential solution sets. In reality the design process has to go through the five stages mentioned above and is depicted more realistically as described earlier in Figure 3, which stresses a continual evolution. The goal of the TQD–driven methodology (as should be the goal of any efficient design process) is to decrease the time spent within the spiral by jumping stages (for example, by developing newer materials and by implementing more efficient technology, and more focussed management approaches). An integrated team rather than a group of individuals is essential to achieving this goal.

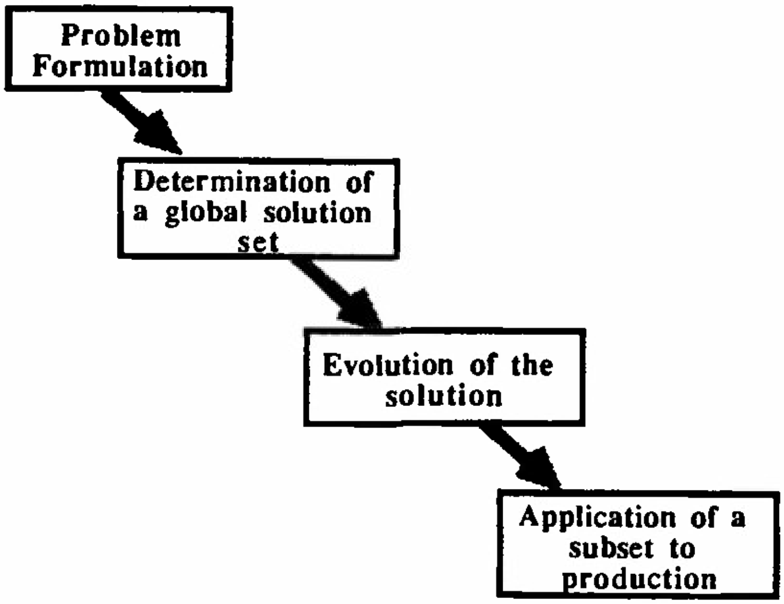


Figure 10: A simplistic "linear" design process

While communication between team members may not be a serious problem to some, almost every engineer would agree that the communication barriers that exist between functional or departmental groups is a serious impediment to rapid product development. Differences in background and technical jargon can create a real 'language' problem. Organizational structure and procedures can also impede the efficient transmission of information. There are three primary types of information — heuristic, analytical, and empirical — and traditional information management involves the collection, storage, and maintenance of large quantities of the latter. With the present advances in communications and computers, it is possible for us to change our thinking about how data and knowledge can be created, stored, and accessed. Unfortunately, the factional nature of advanced technology tends to produce isolated pools of such data available only to the intelligentsia in the originating groups. This pooling of domain specific information is needed for successful implementation of the PRP and is achieved in part through the use of experts, either as members of the development team, or as consultants.

Experts are those decision makers who, through either innate ability or experience, can perform the simultaneous inferencing necessary to come subconsciously, to a balanced technical decision while considering and giving due weight to divergent points of view supported by the incomplete information available. Recall that concurrent engineering is a term that can refer to any engineering process embodying decisions based on relevant factors outside the direct functional responsibility of the project but which, none the less, would be linked by cost schedule or technical challenge during project execution. It is the subconscious evaluation of this linkage, one that occurs across organizational boundaries, technical specialties and project phases that differentiates the expert from the merely competent engineer. For the competent engineer, justifying decisions based on the balanced consideration of numerous and often conflicting priorities, opinions and responsibilities both technical and otherwise, can be overwhelming. In addition, the cost of poor decisions made during the conceptual stages of a project concerning advanced materials (which inherently bear a high cost) can be unexpectedly high (Figure 11).

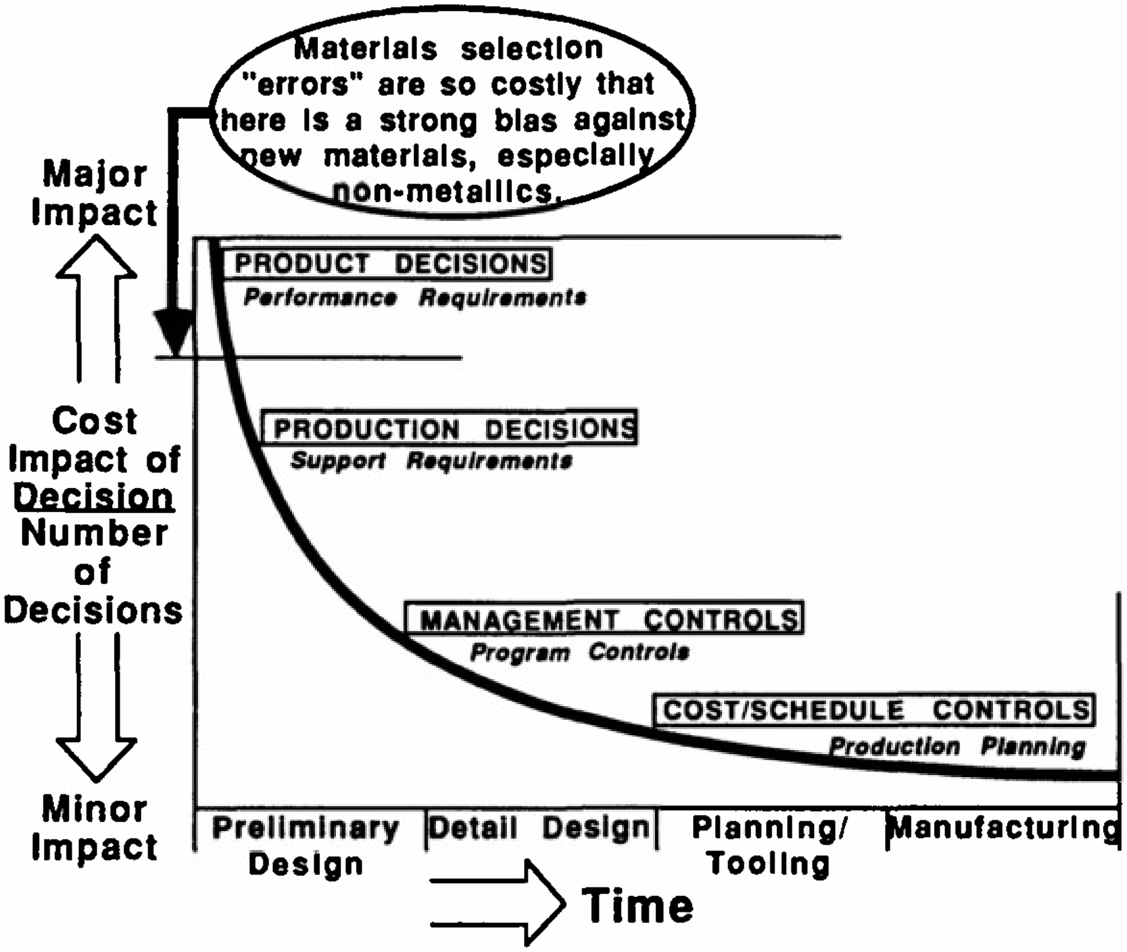


Figure 11: The criticality of early decisions for composites (after Stanton, PDA Engineering)

Complicating the picture still further, eventually the physical records of the information become far less accessible than the experts themselves, who are now integral components of the information infrastructure. Thus, information management and people management converge.

While pooled empirical domain knowledge is critical to the success of engineering design, it is not the only type of information that needs to be collected, stored and used by engineers. Any good design environment will have to incorporate methods to access and interpret all three types of information in an easy and efficient manner. A good facilitation process helps capitalize on the direct, concentrated influence of experts over the design process. Expert systems hold the promise of further enhancing access to domain knowledge pools by providing on-demand, simulated human experts. Whatever the form, it is the use of knowledge that is the heart of the design decision process. The design team needs to anticipate the linkages between the various stages of the PRP, as well as those stages within the PRP at which there is need for concurrency of decisions among a variety of functional aspects. The conscious evaluation of concurrent linkages can be facilitated through the use of the systematic prioritizing techniques embodied in a concurrent, team–based, goal–oriented approach. These tools cannot, however, be used in a vacuum. No tool will, of itself, supply quality to a process. Quality is built into the decision process through the team–building process. A team is the first necessary ingredient to good concurrent engineering solutions, and team building is the quintessential management function.

4.3 THE CRITICAL ELEMENTS

i) The definition:

The Team - The driving force behind any successful product realization process is the team. This group of individuals, when welded together into a cohesive unit, can turn an opportunity into a competitive edge. The accelerating pace and complexity of modern technology makes it imperative that the team be not merely a collection of people but a well–balanced group of experts in the requisite areas. The selection of a mixture of articulate, mentally flexible, diversely experienced members committed to a specific goal or task is extremely difficult but vital to the success of every project. Team building and leadership thus attain great importance, with the nominal leader actually serving as a facilitator (or agent through whom the team functioned is assured) - guiding and ensuring that the team members capabilities are used to the fullest in an atmosphere of loyalty and mutual trust. It is essential that team members be able to compromise, knowing why they did so, and what the team gained in the process. The last is a critical element in the sale of the final concept to the customers - both internal and external. Team building within the context of the TQD methodology is not equally effective for all levels of decision complexity and team size. A realistic reflection of experience to date with these limitations is presented in Figure 12.

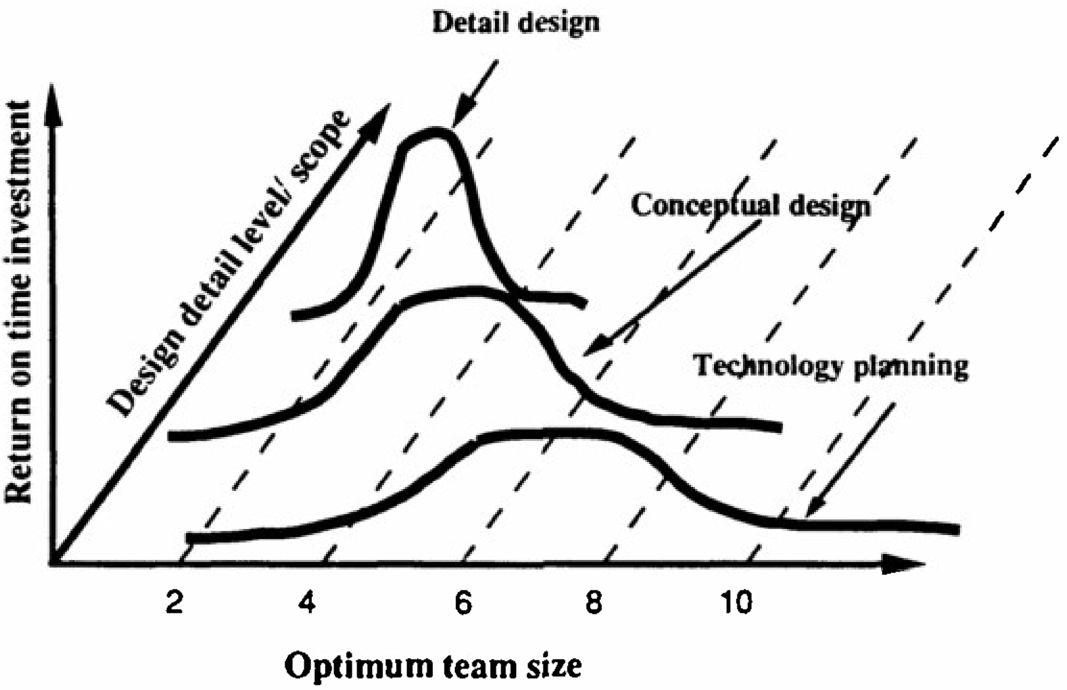


Figure 12: Optimum team size is dictated by project scope

A team of 4-6 people is optimal for many concurrent conceptual design problems; as problem complexity increases through either expanded scope or detail, more of the burden for analyzing compromise must be shifted to smaller groups of more highly qualified team members in order to achieve a reasonable return on an increasingly valuable team's time investment. We stress that the actual number of members in a team is dependent on the scope and specific requirements of the project. The best team member is one that is willing and able to (1) make good decisions within his or her own area of expertise and (2) collect and evaluate information from other team members and outside experts (consultants) for decisions outside their area of expertise. It is in this aspect of concurrent engineering that management emphasis on the human factors of training, motivation and facilitation is required.

Mission Statement - The Mission Statement is, in essence, a mini-proposal from the team to itself, and it serves as the focus for all effort during the PRP. The strategic choices made by management in response to the customer requirements in terms of goals and schedules give meaning and direction to the various activities necessary for the successful development and launch of a product. The mission serves to guide implementation but should be wide enough to permit adaptation and change during development. As a rule it should not anticipate a specific method of solution, thus giving the team full leeway to use the best and most appropriate methods to fulfill their objectives whilst ensuring customer satisfaction. Key to the mission are the criteria of schedule and cost, which together define the scope of a project or program. An effective project team is essential in determining tradeoffs between schedules and costs associated with the mission. All essential constraints and customer imperatives should be included in this two- or three–sentence definition of the team's goal. Relevant information regarding cost, schedule, target market, technical focus and measures of success should be included. The mission statement should figure prominently in all phases of the decision process; periodic review of its guiding features is essential.

ii) The requirements:

Know the customer - Engineering management has long considered customer interaction as a privileged function. As a consequence, several layers of translation often lay between the voice of the customer and the ear of the project team. This has been a major cause of technical nonresponsiveness and an almost assured death sentence for proposed work. It is also an excellent way to earn the ill will of those whose opinions matter most - the customer. The best way to insure customer happiness is to get the customers to personally participate in the team decisions. Quality is defined by the customers and therefore if their direct participation in the activities of the team is not feasible, ensuring the survival of their special points of view can be aided by naming them individually and attaching lists of their specific needs. These lists comprise not only the points they actually discuss but also those points which are so obvious to the customer that they are often omitted from formal dialogue. These customer wants fall under the category of expected quality. Failure to consider an expected quality item will often result in a complete failure of the early decision process. It is essential that the team have a clear understanding, both objective and subjective, of what the customer means by "quality". Garvin [1984] identified five major approaches to the definition of quality and described the ways in which they may be viewed by different functions of the PRP such as marketing and manufacturing. The eight dimensions of quality identified within these approaches are shown in Figure 13. The reader is reminded that some of these may be of greater importance than others. In composites, for example, the attributes related to performance, reliability, durability, and conformance far overshadow the rest.

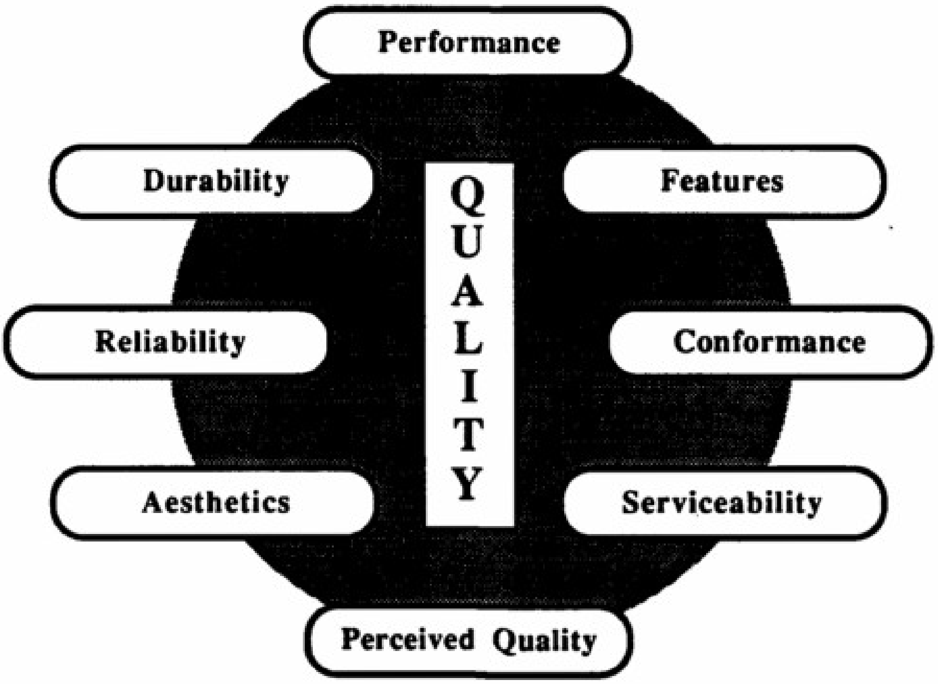


Figure 13: The eight aspects of quality (after Garvin, 1984)

It is essential that the aspects of quality be recognized by the team; team members must realize that they would change according to not only customers but also the specific use of the product and technology. The term *customer* must be understood to include two classes of people. The first set falls within the purview of the traditional definition of a customer - a person outside the specific organization who either buys a product or uses services provided for a cost. The second set is made up of internal customers. These could be teams that are downstream of the function being performed, departments being served by other departments, or even stock-holders. It is the need for the "satisfaction" of the internal set of customers that has caused a paradigm shift of late - the designer must satisfy the production engineer's needs if the product is to be made well, rather than just presenting a design that may or may not be producible based on the specific capabilities and options open to the manufacturing team. Without the support and satisfaction of the internal customers, it is impossible to successfully implement a product development and marketing strategy, let alone satisfy the real customer.

Customer wants - Customer wants are just that - and more. They are the expressed and implicit needs of the customer as discerned from the extensive customer dialogue already mentioned. These wants should comprise a free-form list indexed to the list of specific customers. Prioritizing the customers with regard to which key few must be satisfied will, through this indexing, prioritize the customer wants in preparation for the evolution of metrics. The list should remain as true to the words of the customer as possible to avoid unintentionally biasing their evaluation. It should be remembered that under the new paradigm of customer satisfaction being the ultimate goal of any industry, customer wants are the primary driving functions of product development. Care should be taken to determine these wants, some of which may be intangibles (such as aesthetics), and define them in terms of technical requirements and specifications.

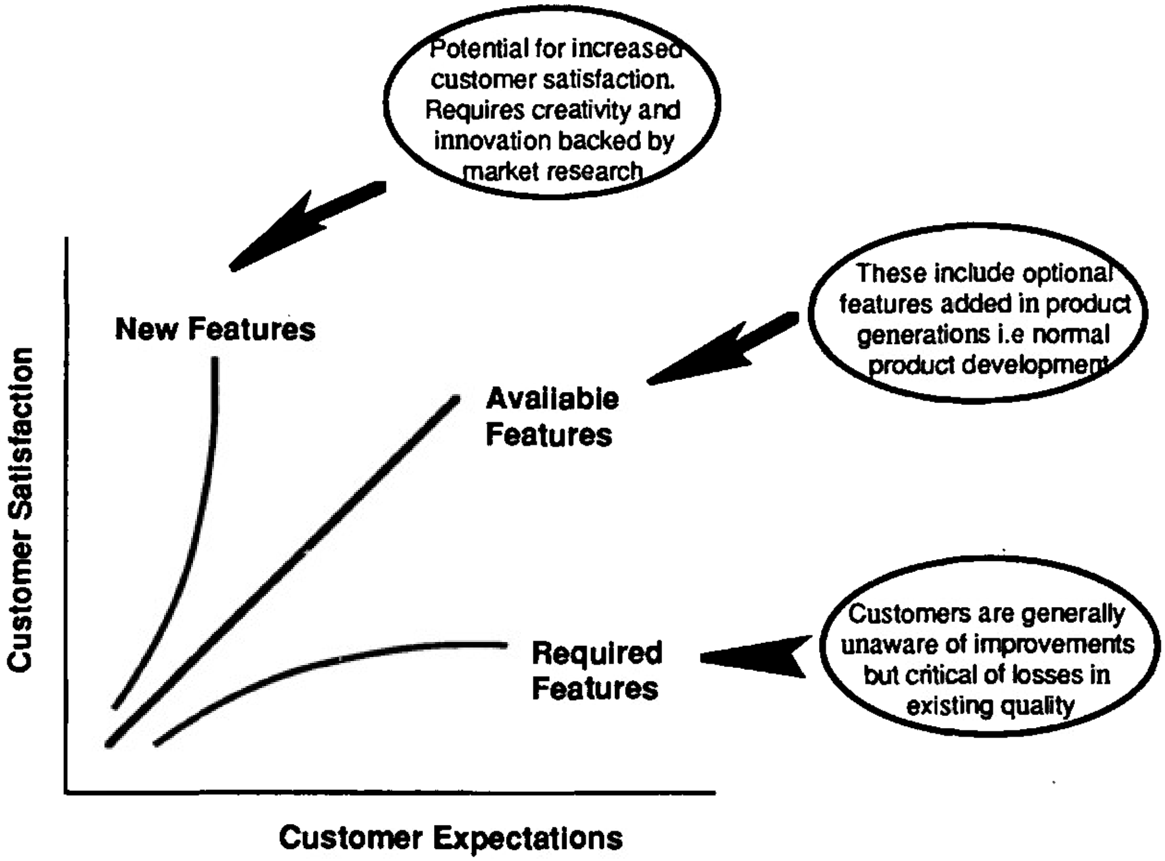


Figure 14: Perceptions of quality associated with customer wants

Quality perception in terms of expectations and satisfaction (Figure 14) need to be carefully considered after benchmarking. In the final analysis the satisfaction of needs and wants is guaranteed if the customers attain their goals at the end of the PRP. With composites, it may be possible to satisfy wants previously unaddressed by established material paradigms through modifications in materials, manufacturing methods, or configuration or a combination of these.

iii) Benchmarking:

The process of benchmarking has been defined as "measuring your performance against that of the best-in-class companies, determining how the best-in-class achieve those performance levels, and using the information as the basis for your own company's targets, strategies, and implementation" [Pryor, 1989]. This process has recently been applied both to product development and to improving the focus and culture of a company [Bemowski, 1991]. It can also serve as a means of understanding the difference between the relative limitations imposed by business practice and the limitations imposed by a theoretical optimum, and, in that vein, is applicable not only to product or service development but also to process and technology development. The use of external measures of success can shift the focus of quality control from merely measuring product attributes to developing detailed descriptions of process steps and work methods to guide future innovation. This investment in the future not only leads to a better understanding of the specific processes but also causes a perceptible shift away from the practice of evaluation in terms of short–range goals with its attendant search for scapegoats at times of failure.

Since most technical innovation is evolutionary in nature, benchmarking the competition is possibly the most rewarding exercise of judgement the project team can make. Benchmarking is a competitive analysis of the merits of pre-existing solutions to similar technical problems posed by similar customers with an eye toward adapting superior concepts to fit the current mission goals. Most companies have some sort of "lessons–learned" program in place; unfortunately, such programs generally focus only on internal product development history, and then only in those technology areas sufficiently reduced to practice, rather than on data correlated from the competing industry in general.

Quality Metrics - Metrics are those measures of engineering success that will translate how well any and all solutions proposed by the team in later phases of the decision process will satisfy the prioritized list of wants, a list which is itself a translation of the true desires of the most important customers. Quantitative measures of success which imply an intrinsic scale are to be preferred over more qualitative measures. Some wants will force the adoption of metrics that are purely qualitative - a sporty look for a car is a common example -

which requires some creative metric formulation. Marketing experience on the team is invaluable in framing the customer dialogue (usually by survey) necessary to obtain unambiguous qualitative metrics. Economic metrics are quantitative but largely unfamiliar to the engineer. Inclusion of an econometric support member on a team concerned with cost performance is generally advisable, as is the use of modern cost-accounting procedures such as activity–based costing. It must be remembered that the choice of quality metrics, which in essence serve as the functions to be benchmarked, is a key element of the entire process -- the transition from customer relations to engineering. The list should include those factors, conditions, or variables that when achieved make the difference between success or failure. These should also include metrics that identify and quantify areas in which improvement is needed. It could be argued that the proper selection of metrics also serves as the first step in setting realistic goals for the PRP. Linking individual metrics to the previously prioritized list of wants will result in a corresponding prioritization of those metrics suitable for the efficient and responsive evaluation of all solution concepts to follow.

iv) Concepts:

Concept Generation - It is essential that, at the outset, a profusion of concepts, some new and others adaptations of existing products or features, be generated. The flow of ideas and concept should be unhindered by formal structure or bias. Creativity and innovation are the keys here . Always remember that there are no dumb concepts, only dumb responses to their suggestion. Design experience may actually hinder the free formulation of innovative solutions; often the novice, unfettered by years of ingrained bias, can bring fresh perspective to the generation of competing solutions. Although this stage is generally considered to be the focal point for creativity, it is stressed that for the best use of any advanced technology, creativity and innovation must be a generic part of the entire product development process, not just at the concept generation phase.

Concept Selection - The large number of concepts generated has to be pared down to the best two or three. Here, the competing concepts are impartially and rationally graded on their ability to satisfy customer wants as expressed in the prioritized list of quality metrics. Where available, a recognized standard of performance, usually a competitor's fully proven solution, should be used as a benchmark in determining the relative merits of team–generated solutions. This benchmark serves to scale the evaluation process while providing a reminder of real-world issues and their successful application. If the field of competing concepts has been narrowed considerably and no clear winner is evident, the strongest surviving concept should be chosen as the benchmark and the remaining concepts rated in relation to this new baseline. At this stage,the most important quality metrics may be used as criteria for deselection of concepts. Deselection is particularly useful when, as often happens, several metrics remain unmeasured because of either time or budget constraints. Comparative analysis of alternatives, besides being fast, also sharpens preferences through the use of rankings [Eisenhardt, 1990] so that the superiority or desirability of one concept over others becomes clear, even if the actual difference cannot be quantified. Details of this approach as well as one possible implementation of its methodology in electronic form as part of a decision support system are given in [Karbhari and Wilkins, 1991; Karbhari et al., 1991]. Often, not knowing how an unresolved metric will turn out is enough to disqualify a concept, especially if even a wildly favorable rating will not negate other, more persuasive, arguments against the concept. Technological uncertainties are a major reason for the delay in a PRP. The team has to protect itself from falling prey to the desire to incorporate the latest technological improvement into the product, especially when its compatability and/or reliability has not been proven. The Go/No-Go reviews, among their other purposes, provide an opportunity for the team to ensure that this does not occur.

v) Go/No-Go Reviews:

At the end of concept selection, management and the team have to decide whether it is worthwhile to further develop a concept. The TQD process recognizes that product innovation and development are processes that need to be managed. The Go/No-Go reviews serve as gates at which critical assessments must be made.The Go/No-Go review is the critical decision point in the product development process. If the decision is a "Go" both management and the team have determined with a high degree of confidence that further development expenditures are justifiable. If the decision is a "No-Go," management and the team have automatically identified the technology gaps, economic issues, and competition conditions that make further development imprudent. In fact, the "No-Go" decisions are critical for defining the research and development (R&D) agenda for the company. If the company is aggressive enough in pushing the state of the art in production, "No-Go" decisions should result from a high percentage of TQD projects at the first instance. This in no way suggests a failure of the PRP. Rather, it ensures that every design is completely evaluated and, once past the review gate, would have a high probability of success.

Thus, the idea of completing TQD projects in a number of days or weeks creates a rich atmosphere of new concepts and an urgency to improve them, and include them in the product under consideration. The use of these reviews is analogous to the stage-gate system recommended by Cooper [1990]. The use of "gates" (or Go/No-Go reviews) is an implicit recognition that product development is a process rather than a set of disconnected stages. The Go/No-Go reviews (Figure 15) serve as quality checkpoints, characterized by a set of deliverables.

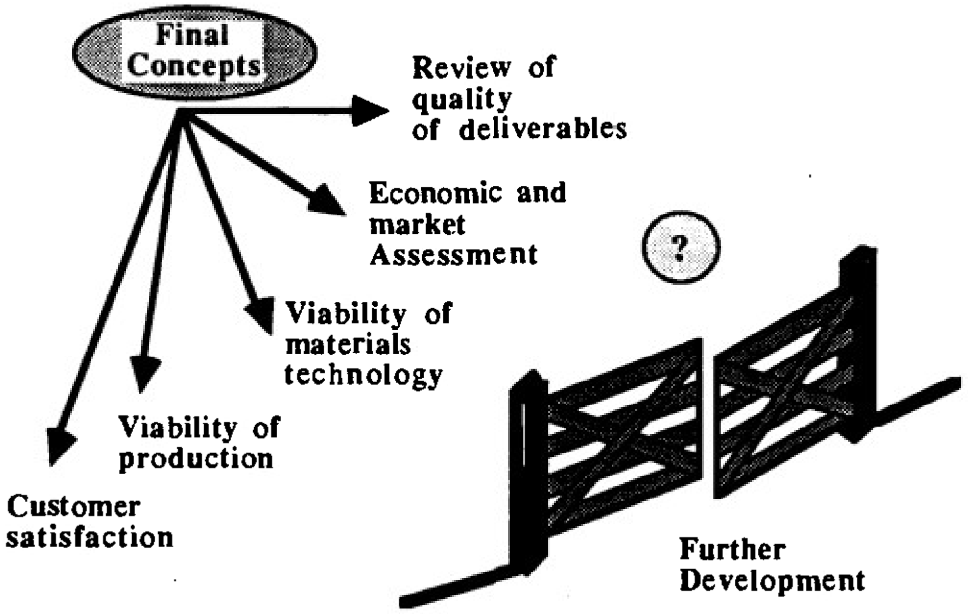


Figure 15: The Go/No-Go review as a gate in the Product Realization Process

Each such review can be characterized in terms of (1) questions regarding product feasibility and viability as inputs and (2) a set of exit criteria drawn from the quality metrics and design profile constructed from the mission statement and list of customer wants. Further details are given in the TQD Workbook attached as Appendix 1. A set of electronic templates that can be used to aid a team follow the methodology in picking the right concept is enclosed in Disc 1. The use manual is attached as Appendix 2.

5. TOOLS FOR DECISION SUPPORT

One of the biggest problems with engineering design today is that we are unable to represent the world perfectly in terms of mathematics. While communication between team members may not be a serious problem to some, almost every engineer would agree that the communication barriers that exist between functional or departmental groups is a serious impediment to rapid product development. Differences in background and technical jargon can create a real 'language' problem. Organizational structure and procedures can also impede the efficient transmission of information. Of the three types of information — empirical, analytical, and heuristic — traditional information management involves the collection, storage, and maintenance of large quantities of empirical data. While this type of information is critical to the success of engineering design, it is not the only type of information that needs to be collected, stored and used by engineers. Any good design environment will have to incorporate methods to deal with all three types of information in an easy and efficient manner. With the present advances in communications and computers, it is possible for us to change our thinking about how data and knowledge can be created, stored, and accessed.

5.1 KNOWLEDGE REPRESENTATION:

Knowledge, in reference to design can be classified into four categories, namely factual, procedural, judgmental, and control related [Rasdorf, 1985]. All four categories are of importance to decision making for composites design and manufacture. If we were to relate the representation of knowledge through electronic media such as computers, we would be faced with a set of five storage and access alternatives. Each of these is briefly discussed below.

a) MODEL BASES (ANALYTICAL DATA) - Analytical data is the information embodied by our understanding of the laws of nature and the information derived directly from these laws. This information is at the opposite end of the scale from empirical data. While empirical data is very concrete (but not necessarily accurate), analytical data is very abstract (but also not necessarily accurate). Typically this information is expressed in the notation of mathematics and is generally coded directly into a program. Much work needs to be done in order to separate this type of information from the control procedures and algorithms encoded by computer programs. If this information is available directly to the engineer, then he can direct the type of analysis performed. The development of predictive capabilities through the use of simulations, and analytical models can go a long way towards decreasing the high costs involved with current programs aimed at characterization of materials, and the viability testing of processes. Computational research leading to the development of such tools can go a long way towards acceleration of the manufacturing process. An example of such knowledge based tools is the use of computational models for mold filling for processes such as Liquid Molding and Injection molding, which help in the design of the tool itself, as well as in the selection of a process window for the application. Figure 16 depicts the use of one such code that has been used successfully in prediction of resin infusion through preforms, as well as in deciding gating and venting arrangements in the Liquid Molding Process [Aoyagi et al., 1991].

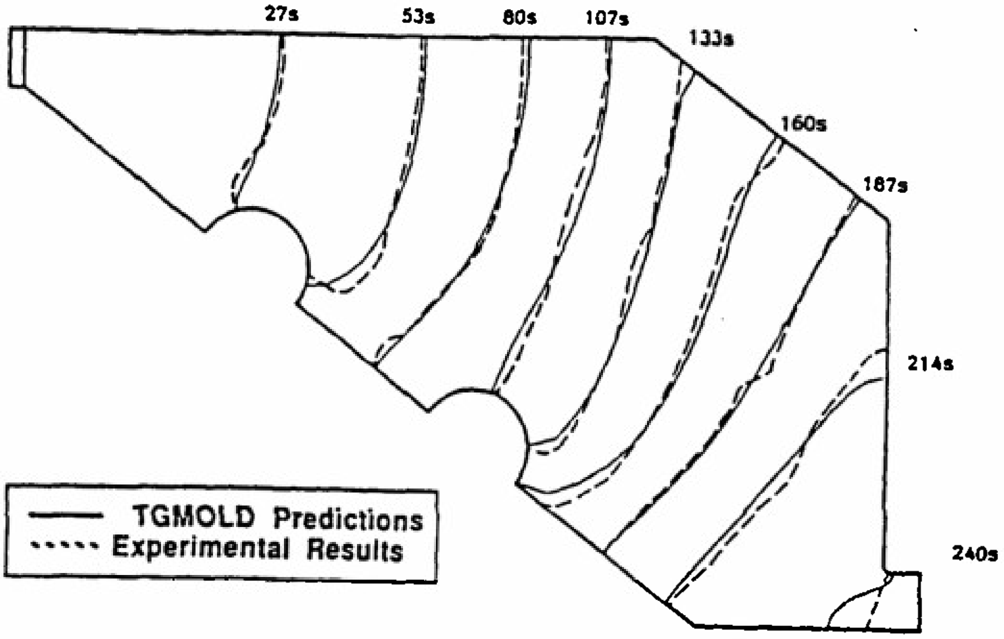


Figure 16: Simulation of the resin front in an RTM process (courtesey Dr. S.I. Güçeri)

However it is necessary that the limitations of these models both in terms of the limited set of parameters used, as well as in terms of the simplifying assumptions are made clear to the user. An important aspect that remains today, is the structuring of different model bases such that they could all be integrated into one system.

b) TEXT BASES (ANECDOTAL KNOWLEDGE) - Although one of the primary forms, and perhaps the most used, of methods for the storage of data, this form is unwieldy for purposes of design and decision making. This is most commonly used for the storage of technical articles and texts for easy retrieval and access. However, their main use is educational and instructional, rather than as an aid to decision making. An added disadvantage is that data stored in this format does not follow a uniform pattern, in that it encompasses text, pictures, equations, and numerical data, all of which though important, make the actual uncovering of critical information cumbersome and time intensive.

c) DATA BASES (EMPIRICAL KNOWLEDGE) - Empirical data is typically thought of as just plain numbers. This is the type of information obtained when we measure and tabulate or graph as the result of experiments. It is also the type of information that is stored as characters on a page, like names, dates, places. This information is often stored in databases, but can also be stored directly as part of an algorithm in a computer. The biggest problems with empirical data are obtaining accurate data and maintaining the database, i.e. keeping it up to date. An example of empirical data is given in Table 1, in which data related to the Weibull modulus, diameter and standard deviation are given for a number of types of carbon fiber.

Fiber Designation	Weibull Modulus	Diameter (microns)	Standard Deviation
AS-4	4.5-5.4	7.9	0.44
Apollo IM	4.7	5.5	0.23
ACIF-XHT	5.6	7.4	0.32
ACIF-HM	4.2	7.4	0.31
M40	5.0	4.8	0.25
M55	7.5	4.7	0.20

Table 1: Example of numerical data likely to be found in a data base

Although the data is accurate at the time it was generated, better control over the fiber manufacturing process could conceivably result in changes in Weibull modulus values and lower values of standard deviation of diameters within the same batch. It is essential that such information is constantly updated if it is to be used with any degree of accuracy. These are problems that must be solved through organizational means and can not be automated to any great extent. For the design environment of the future to reach its full potential, databases for material constants, previous designs, parts, systems and competitive benchmarks must be constructed and maintained. Engineers rely heavily on empirical data and will need to have quick access to accurate information. In addition to just storing this information, the source of the information should also be stored. Material constants should be labeled with the source of the data so that the engineer can simply query the data for its source. Likewise, every decision made in a design, every tolerance, dimension or form, will be tagged with the name of the program or engineer who determined the numerical value along with the date and reasons for the decision. This documentation will be valuable for determining why a given tolerance or dimension was assigned when it becomes necessary to make changes. Currently a number of databases are available online that deal with material properties. Standardization is however, an issue that still needs to be resolved. A standardization initiative is underway in this country, with a uniform designation system, a unified testing matrix, a verification methodology, and a standardized database as its basic goals. It has been endorsed by a number of key organizations, including ASTM, SACMA, SAE, AIA, and DOD, but implementation is still an issue of the future [Wilson, 1989]. Although databases are generally considered to be concerned with numerical data, they may include collections of facts rather than figures.

d) RULE BASES - These are generally considered the domain of Artificial Intelligence, and complement the data available in model and data bases. The most outstanding use of such rule based systems has been in the medical diagnosis area, where a comprehensive set of "if - then" statements helps to guide the doctor in making a diagnosis in the shortest possible time. One reason why this has still not been used in composites design (although significant use has been seen in the analysis of composite structures) is that the wide number of choices and the lack of a clear hierarchy of decisions, makes it near impossible to construct all but a very fundamental and specific system. The decision support system being envisaged would use the rule base to connect different discriminators (as described in the next section) so as to enable the deselection of concepts that are unsuitable to the set of performance attributes specified for the application. It is possible to string together a set of rules that would allow the selection of a process based on the requirements of the application, as specified through discriminators such as shape, microstructure, number of parts etc. For example:

If PROCESSING TEMPERATURE = LOW then RESIN = THERMOSET

would discriminate between the matrix materials. A set of linked questions could be as

If TWO SIDED SURFACE FINISH = GOOD
and SHAPE = COMPLEX
and MICROSTRUCTURE TAILORABILITY = HIGH
then PROCESS = RTM

This use of this procedure however assumes that sufficient information is available in the form of YES/NO rules. Most rule-based systems then are based on heuristic data. In fact the argument can be made that all knowledge is heuristic. Rules of thumb are the prototypical example of heuristic data. Many scientists, researchers and computer scientists abhor the use of heuristic data because it is not purely a measured quantity nor is it an abstract principle or law. While much heuristic information can be represented by numbers and mathematical equations, it is much more frequently realized as if...then...else type statements. This type of information is very difficult to extract, store and manipulate, except through the use of expert systems. Special paradigms called inference engines have been developed to begin to deal with the wealth of heuristic knowledge that an engineer needs to use every day. Prototype expert systems based on such heuristic information is currently being used for the development and control of autoclave curing of composites [Abrams, 1987; Beris et. al, 1991; Lee and Abrams, 1990] and in relating defects to autoclave process conditions [Kliner, 1991].

e) IMAGE BASES - Although not widely used as yet, the advances in image processing and data storage have made this form of data very attractive. The use of image bases adds another dimension to the idea of a decision support system being a highly visual, object-oriented system that would allow users to incrementally describe their specifications, using the image base to view previous artifacts in order to construct a new prototype.

The design environment of the future will incorporate heuristic knowledge seamlessly throughout in the form of expert advisors. These programs will respond only to an engineer's request for information or analysis and not be constantly overseeing the design. These programs will behave like a mentor, not as a design team member. However, we are still far away from being able to actually implement these systems, and it is the thesis of this paper that heuristics by themselves, without an inference engine can be used within a design environment as decision making tools. These then, used in combination, are the basis for the conceptualized decision support system for composites.

5.2 DECISION SUPPORT SYSTEMS

Research in the areas of human decision making has indicated that although human capabilities in complex decision problems are rather limited [Slovic et al., 1977], experts adapt to specific types of problems rather quickly. They simplify the problem through the use of heuristics gained through experience or collected over the years [Russo and Dosher, 1976]. It is towards the goal of (a) assistance in structuring a complex problem, and (b) assistance in extracting preferences within a predetermined framework that computer based decision making systems have found the most use. The main goal then is not focussed on the system of information flow as in a Management Information System, or on specific problem solving techniques (as in an expert system), but in providing decision makers with a set of tools for interactively exploring, designing, and analyzing criteria. Ideally, a DSS behaves like an expert or consultant, in that it supports the decision maker in understanding, expressing, structuring, and analyzing a problem.

It is essential that we make a distinction between an expert system and a decision support system. The decision support system is not expected to replace the expert or provide complete answers. It is however, expected to support decision makers in expressing (through the use of text and image bases), structuring (through the use of rule bases), and understanding (through the use of data, rule, and model bases) the problem under consideration. Its function can then be viewed as that of increasing the effectiveness of decision makers in situations where the use of stored information could support and/or enhance human judgement. It thus is a means of providing decision makers with appropriate tools for "interactively exploring, designing, and analyzing decision situations in a manner compatible with their mental representations" [Angehrn and Lüthi, 1990].

For the type of problem inherent in composites design, the "ideal" system would be based on the aggregate experience of a number of experts in the field who have extensive experience in making such decisions in response to the product development process. Once specifications have been determined and potential alternatives identified, the system should be able to provide "trace-back" capabilities, so that the user can see exactly how and why the alternatives were arrived at, i.e., what was the sequence of decisions, and how were they linked in order to lead to the particular option? This would not only give the user the option of using it as a decision making tool, but also as an educational one. Finally the DSS should be able to perform "what if" analyses regarding how a change in an earlier decision affects other intermediate decisions, or the final decision. For example, one type of heuristic decision model is described by Tversky [14] as "elimination-by-aspect." An elimination-by-aspect model allows the user to specify a minimum acceptable level for each attribute (such as strength, toughness, etc.), and also the order of importance of the attributes. Then any alternative not meeting this minimum level for each attribute (the attributes being arranged in decreasing order of importance/priority) is eliminated from further consideration. Although such systems have been constructed in the past, they have all fallen short of being able to provide the capabilities of allowing tradeoffs to be made so as to include alternatives that would otherwise have been eliminated due to a minor shortcoming on one attribute. The implementation of a solution to this shortcoming is described in a later section. Not only does the proposed system help the user in recognizing the various stages in a manufacturing process and the choices involved at each, but it will also enable him or her to conduct "what if" analysis regarding how a decision early in the process directly affects options further down in the product or materials development process.

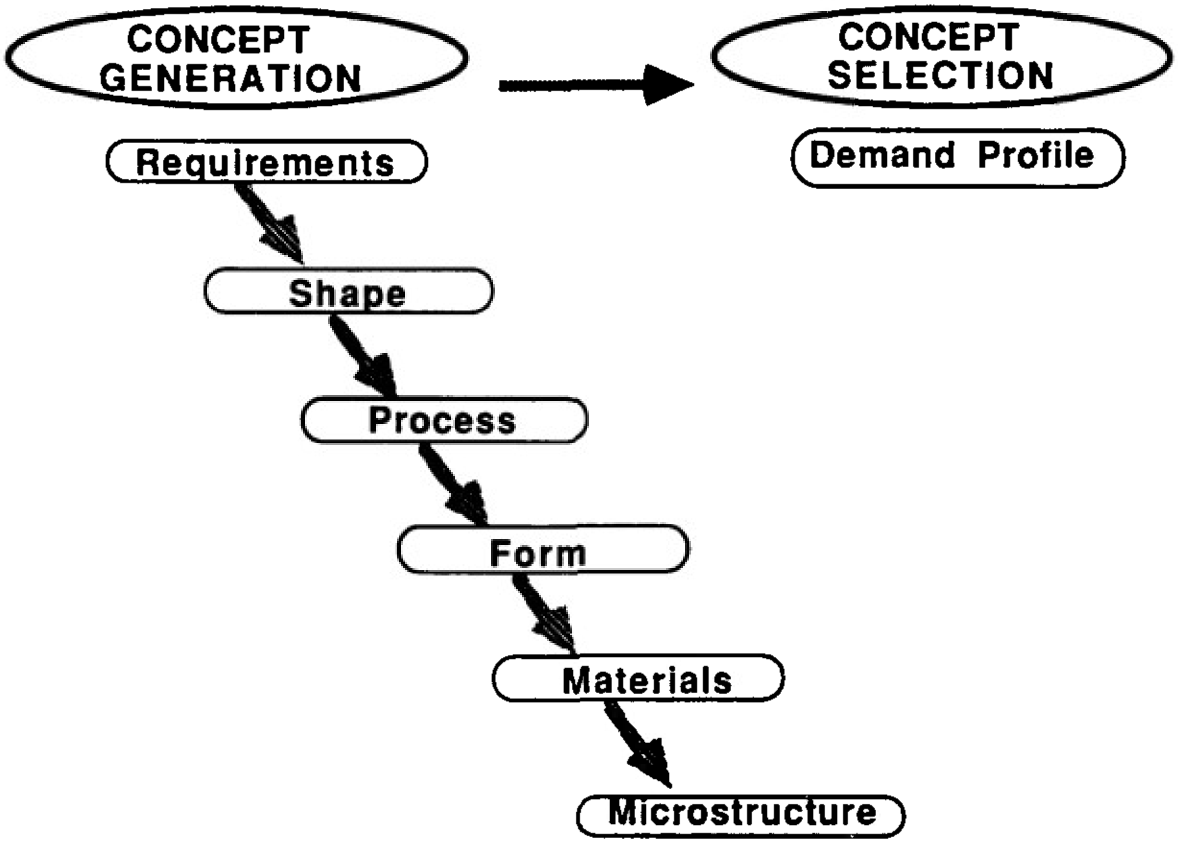


Figure 16: An example of a design hierarchy

Figure 16 shows an example of a design hierarchy. Although shown in linear form it is clear that the choice of an element at any of the levels affects choices both above and below that level. The choice of process for example will be affected by the shape required (but will in turn affect the selection of a shape primitive if for economic or other reasons, a specific process is fixed), and it will also affect the form, selection of materials, and resultant microstructure. If we were to choose the pultrusion process, we would be limited to simple shapes with constant cross-section and limited flexibility in microstructure. The requirement of finely tailored microstructure, would however result in the selection of the Resin Transfer Molding process, which due to current capabilities would restrict the choice of resin systems to the thermoset family. Although such data is thought to be of an obvious nature, it surprisingly is not so. In a recent report based on a survey to evaluate UK designers familiarity with materials, it was found that there was a "widespread lack of knowledge of modern materials and processing techniques" [Hayes, 1990]. More often than not, this ignorance results in disappointing performance from a prototype, exorbitantly high costs, and the ultimate abandonment of the composites effort, resulting in the loss of competitiveness.

In the following section we present a scheme that is being implemented using a HyperCard® medium within a Macintosh environment. The actual HyperCard® stack is enclosed on Disc 2.

5.3 THE CURRENT ELECTRONIC ENVIRONMENT:

Composites manufacturing can be thought of as a materials transformation process, made up of a sequence of steps.

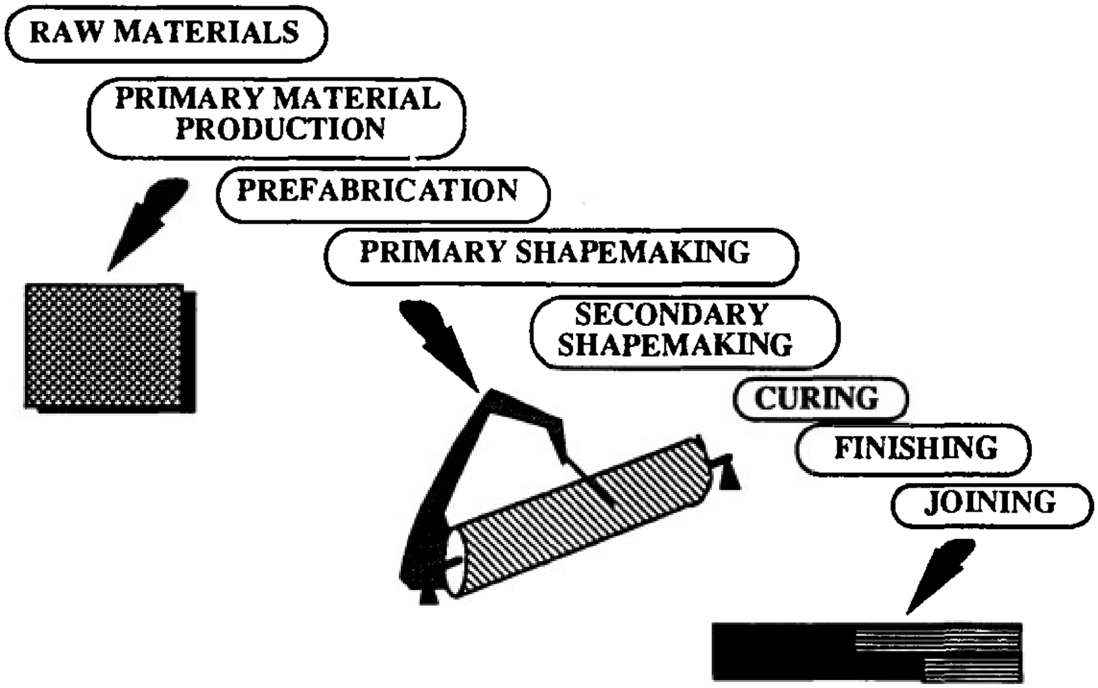
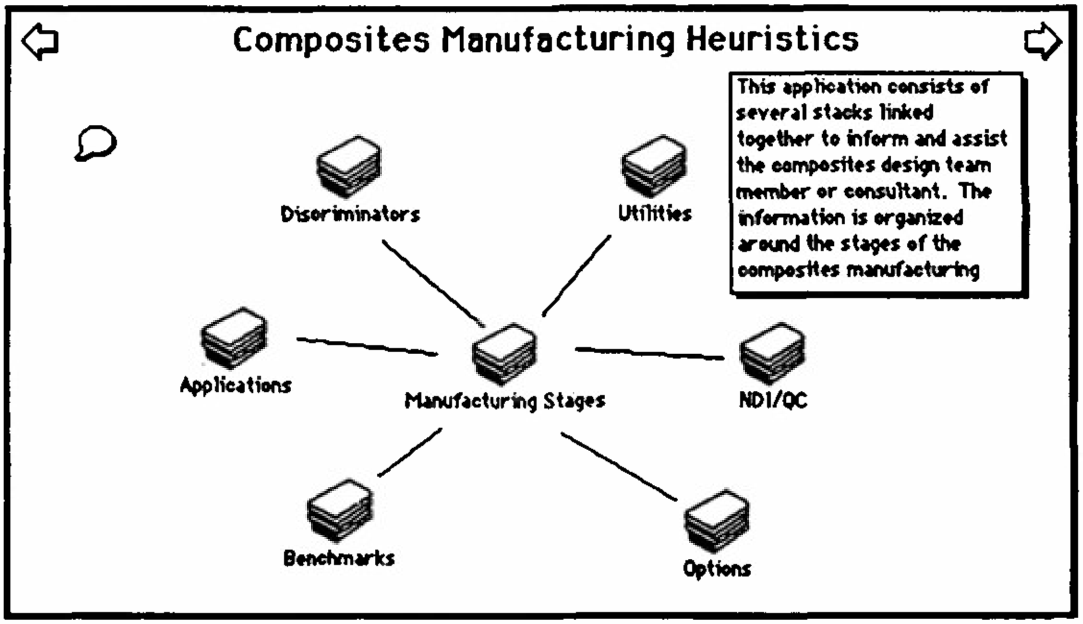


Figure 17: The materials transformation process (MTP)

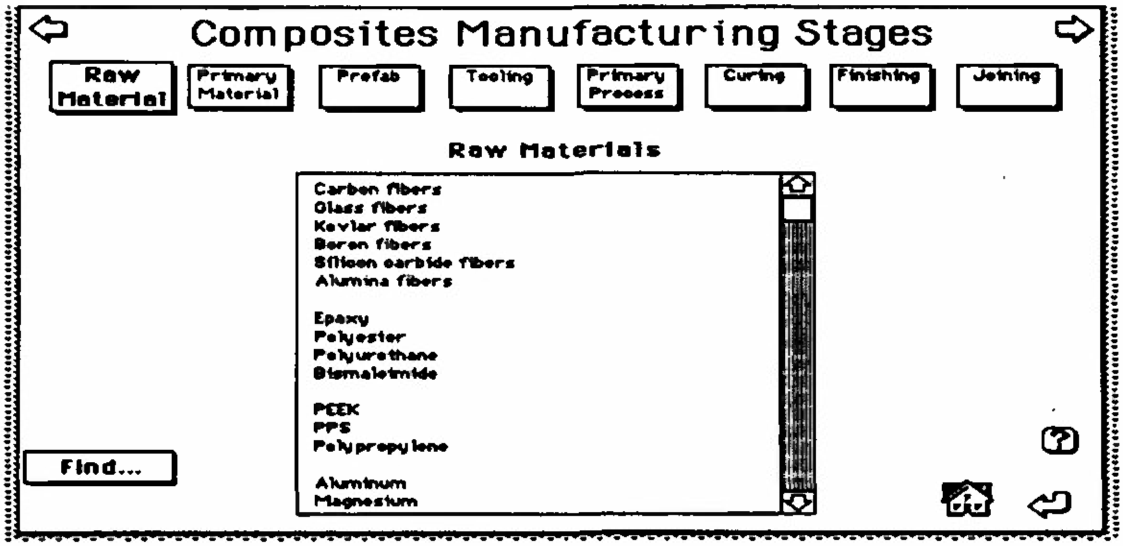
Examples of such steps are raw material production, primary material production, prefabrication, tooling, primary processing, curing or post-processing, finishing, and joining (Figure 17). Within each step, there are a number of choices (including the possibility of skipping the step). It is almost impossible, even for the most experienced designer, to list without omission, all the steps and the various options within each step, for every manufacturing process. The construction of such a knowledge base in electronic form allows the design team the opportunity of looking at a spectrum of possibilities for the fabrication of a composite structure. Such a system would enable design teams to consider options that would normally be deemed undesirable, but which could be successfully used within special environments. Examples of this have been seen to arise due to the availability of unique combinations of tools, equipment, and experience at fabrication sites. Such special cases would be neglected or rejected through the use of expert systems, whereas decision support systems have been seen to bring such options to the fore.



This application consists of several stacks linked together to inform and assist the composites design team member or consultant. The information is organized around the stages of the composites manufacturing

Figure 18: HyperCard® based representation of the set of options available in the existing DSS.

In order to place the latest information regarding options at each stage of the materials transformation process for composites at the disposal of the design team, the DSS is built around the MANUFACTURING STAGES stack as shown in Figure 18. The options that feed into the central stack provide supporting and/or more detailed information to the design team. The UTILITIES stack stores HELP type information on the use of the DSS and the other stacks. The APPLICATIONS stack is a repository for images and data from completed projects. The user has the facility of adding in customized data and retrieving it in a variety of ways for further use in routine or innovative design. The BENCHMARKS stack serves as an easy access to lists of suppliers and services as well as references to literature. Retrieval from this can be in numerous ways and can be accessed from within the MANUFACTURING STAGES stack. The OPTIONS stack serves as a guide or map for the user. The NDI/QC stack contains information related to non-destructive inspection methods and quality control procedures. This stack serves both as a reference as well as an educational tool. Approaches such as Statistical Process Control (SPC) and Taguchi methods would be explained in this stack and it is envisaged that this stack would be used to link the team to a set of SPC tools and software routines directly. The DISCRIMINATORS stack contains information in the form of tables or graphic charts that allow the user (or design team) to compare and contrast different options. The comparison of materials, processes, or even concepts based on specific quality metrics allows the design team to narrow down its options in an efficient manner. The use of this will be further elucidated in a later section. All the stacks can be accessed from within the MANUFACTURING STAGES stack, as well as independently. We will focus on the MANUFACTURING STAGES stack in further discussions, using that as an example to elucidate the scheme.



Carben fibers
Glass fibers
Kevlar fibers
Boron fibers
Silicon carbide fibers
Alumina fibers

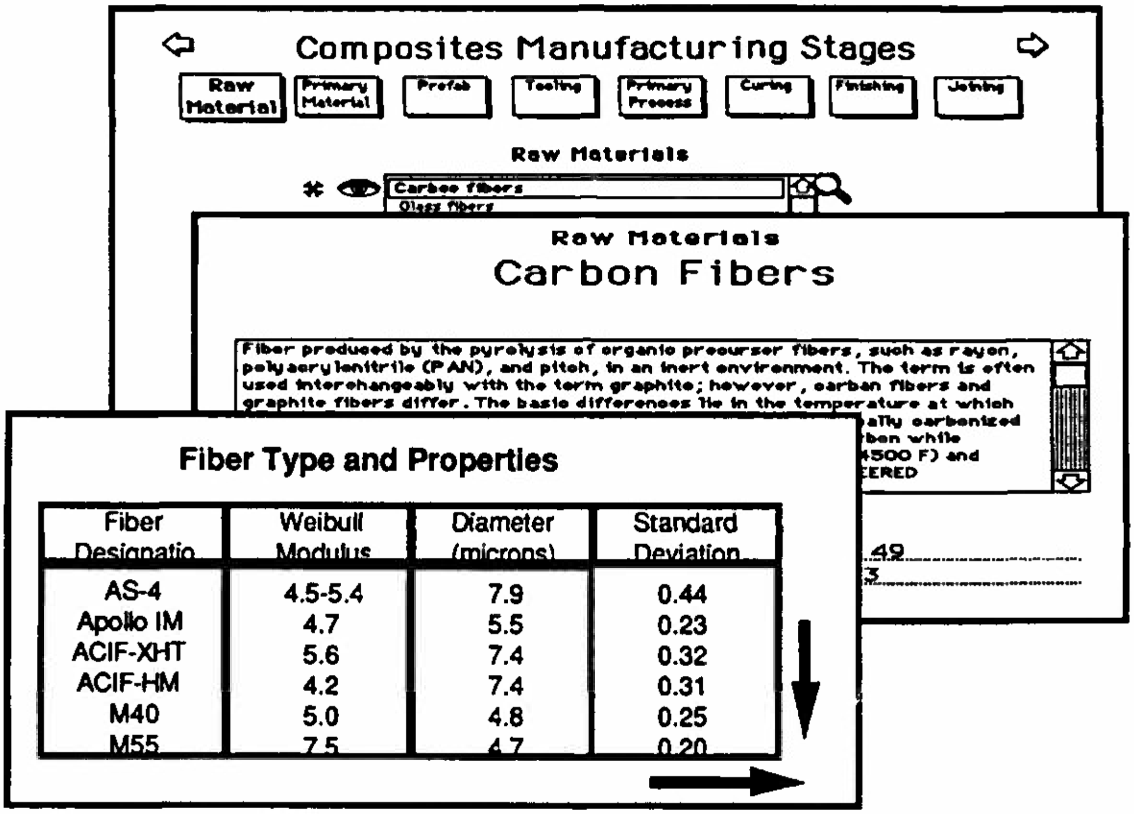
Epoxy
Polyester
Polyurethane
Bismaleimide

PEEK
PPS
Polypropylene

Aluminum
Magnesium

Figure 19: HyperCard® based representation of the materials transformation process

Figure 19 depicts the individual stages of the composites manufacturing process as buttons in a row on top. In this example the RAW MATERIAL option is highlighted signifying that it is being used. The central window shows the alternatives available within the stage of the transformation process chosen. As would be necessary for the selection of raw materials, the different fibers and matrices are listed in the central window. The user can then click on a specific material and obtain further information on it as shown in Figure 20.

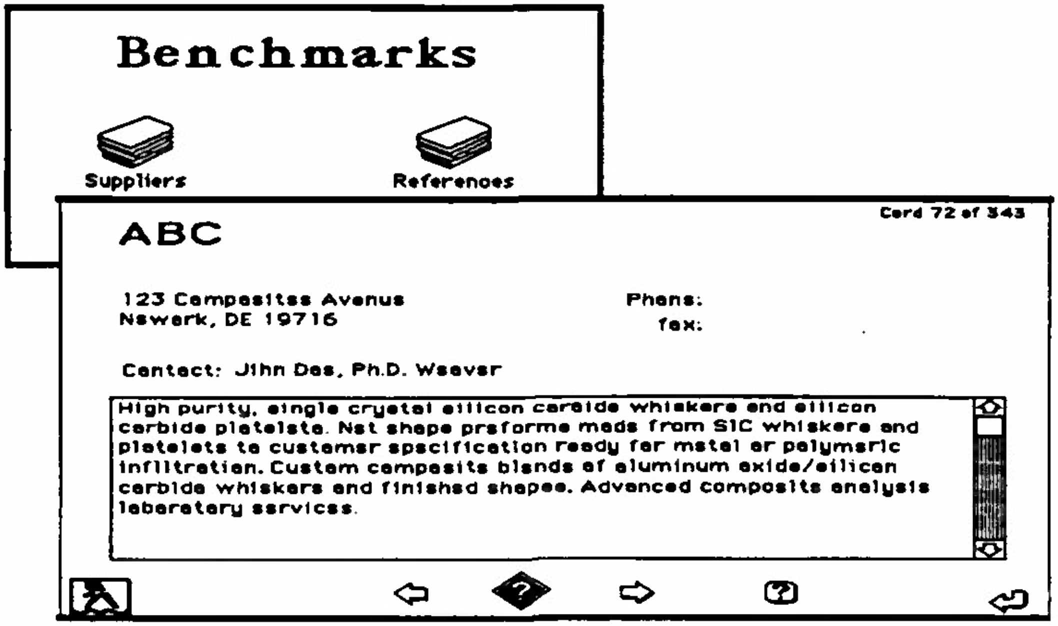


Fiber produced by the pyrolysis of organic precursor fibers, such as rayon, polyacrylonitrile (PAN), and pitch, in an inert environment. The term is often used interchangeably with the term graphite; however, carbon fibers and graphite fibers differ. The basic differences lie in the temperature at which
ally carbonized
bon while
500 F) and
ERED

Fiber Designatio	Weibull Modulus	Diameter (microns)	Standard Deviation
AS-4	4.5-5.4	7.9	0.44
Apollo IM	4.7	5.5	0.23
ACIF-XHT	5.6	7.4	0.32
ACIF-HM	4.2	7.4	0.31
M40	5.0	4.8	0.25
M55	7.5	4.7	0.20

Figure 20: An example of the range of information retrieval possible

In this case the CARBON FIBER option was used, wherein it is possible to get basic information on the fiber both in the form of text with a list of references, and through numeric data on different forms of the fiber. Further information on suppliers and references could be obtained through the interactive scanning of the BENCHMARKS stacks. An example highlighting the use of supplier information is given in Figure 21. If continuously upgraded on linked to a commercial materials database, it is possible to interface the stack so that current cost information is also made available.



ABC

123 Composites Avenue
Newark, DE 19716

Phone:
fax:

Contact: John Doe, Ph.D. Weaver

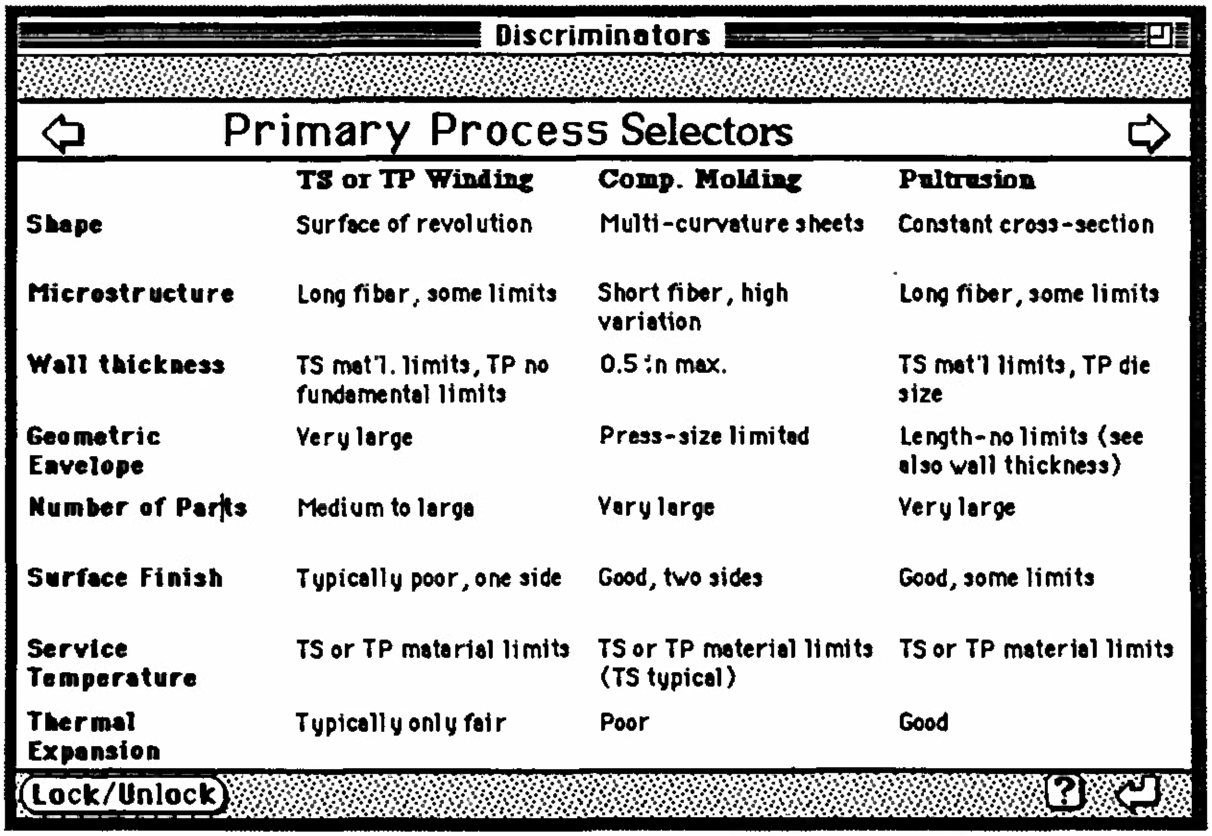
High purity, single crystal silicon carbide whiskers and silicon carbide platelets. Net shape preforms made from SiC whiskers and platelets to customer specification ready for metal or polymeric infiltration. Custom composite blends of aluminum oxide/silicon carbide whiskers and finished shapes. Advanced composite analysis laboratory services.

Figure 21: The benchmarking feature

5.4 THE DISCRIMINATOR STACK

Although the information retrieval process described in the previous section serves as a means for gaining a deeper knowledge about any step in the design process, and serves as a focal point for the design team, it falls short of aiding in the discrimination process. Since the PRP for a composite artifact could conceivably follow a number of routes, it is essential that the design team be able to efficiently discriminate between various options. However, the discrimination process should be such as to allow the team to view other options, thus allowing for the generation of new concepts through the synthesis of older ones. This is in line with the method of "controlled convergence" advocated by Pugh [Pugh, 1990].

In many cases "top-level" information is sufficient to eliminate a number of concepts from further investigation and consideration. One way of facilitating this is through the use of charts as shown in Figures 22, 23 and 24. These allow the user to quickly scan through different options and deselect those that do not meet the criteria as marked by the discriminators (or quality metrics). The nine metrics used in these charts were earlier identified by Henshaw [Henshaw, 1989] as being the critical process discriminators. Obviously this list is not all-inclusive, but does serve to divide the set of all feasible primary processes into the distinct sets of those that are viable under a given set of requirements, and those that are not.



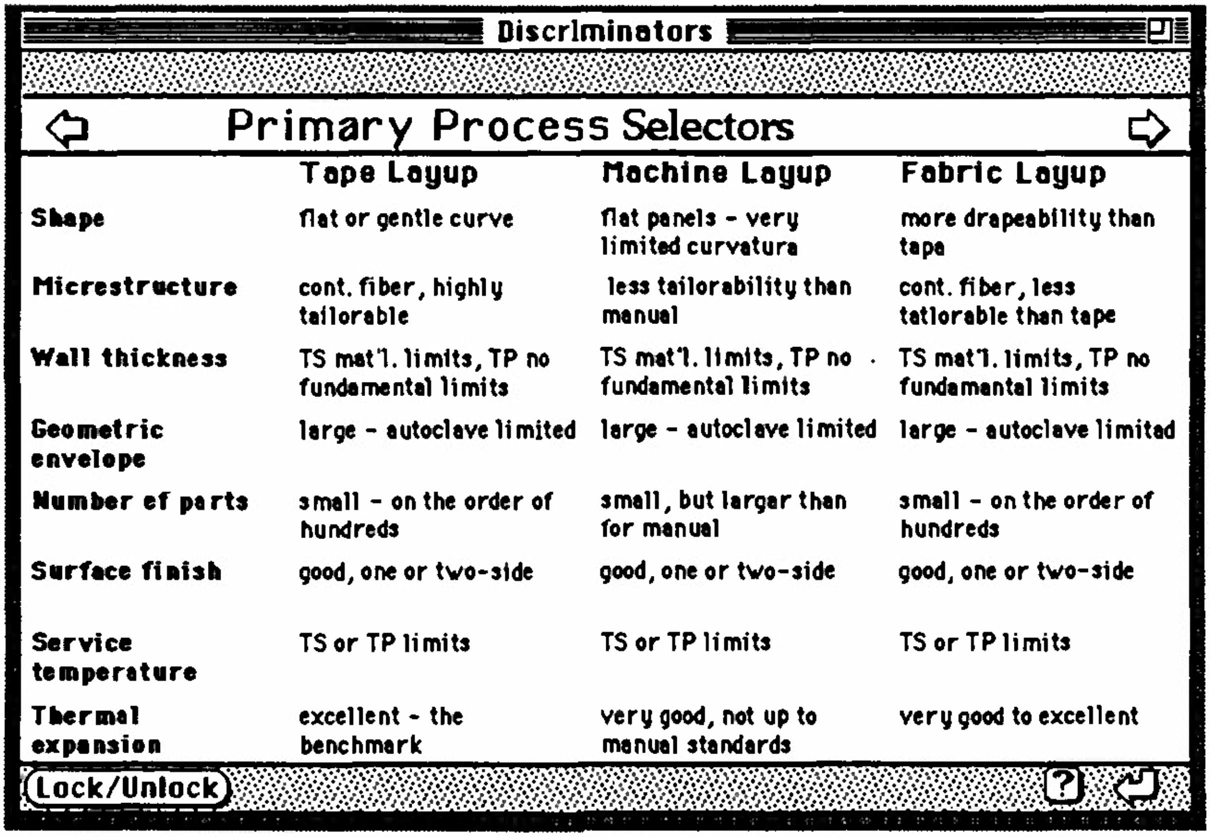
Primary Process Selectors

	TS or TP Winding	Comp. Molding	Pultrusion
Shape	Surface of revolution	Multi-curvature sheets	Constant cross-section
Microstructure	Long fiber, some limits	Short fiber, high variation	Long fiber, some limits
Wall thickness	TS mat'l. limits, TP no fundamental limits	0.5 in max.	TS mat'l limits, TP die size
Geometric Envelope	Very large	Press-size limited	Length-no limits (see also wall thickness)
Number of Parts	Medium to large	Very large	Very large
Surface Finish	Typically poor, one side	Good, two sides	Good, some limits
Service Temperature	TS or TP material limits	TS or TP material limits (TS typical)	TS or TP material limits
Thermal Expansion	Typically only fair	Poor	Good

Figure 22: Discrimination of primary processes

A list as shown in Figure 24 can either be viewed by itself or can be accessed through "clicking" on the appropriate discrimination metric (in this case - microstructure) in schemes as in Figure 22 and 23. This arrangement provides for both additional screening information by itself, as well as linked information between manufacturing stages, so as to facilitate decision making.

Top level discriminators such as the ones shown in the examples above are very useful in the stages of concept generation and synthesis. Most of the metrics are based on heuristics rather than on models or simulations, since the stage of conceptual design is largely characterized by a loosely defined set of requirements, rather than a tight set of performance attributes and bounds. The interested reader is directed to [Henshaw, 1989] for a more in-depth analysis of the use of these specific discriminators.



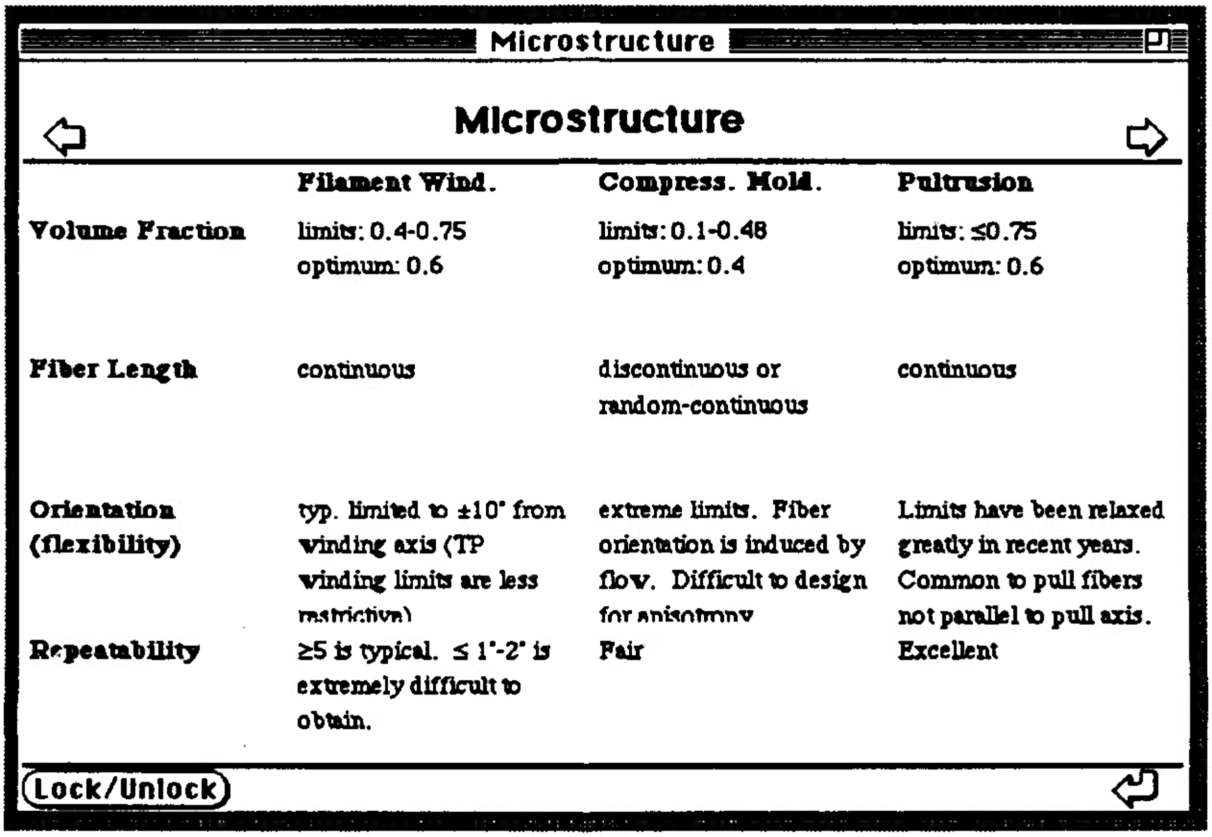
Primary Process Selectors

	Tape Layup	Machine Layup	Fabric Layup
Shape	flat or gentle curve	flat panels - very limited curvature	more drapeability than tape
Microstructure	cont. fiber, highly tailorable	less tailorability than manual	cont. fiber, less tailorable than tape
Wall thickness	TS mat'l. limits, TP no fundamental limits	TS mat'l. limits, TP no fundamental limits	TS mat'l. limits, TP no fundamental limits
Geometric envelope	large - autoclave limited	large - autoclave limited	large - autoclave limited
Number of parts	small - on the order of hundreds	small, but larger than for manual	small - on the order of hundreds
Surface finish	good, one or two-side	good, one or two-side	good, one or two-side
Service temperature	TS or TP limits	TS or TP limits	TS or TP limits
Thermal expansion	excellent - the benchmark	very good, not up to manual standards	very good to excellent

Figure 23: Discrimination of primary processes

It is the authors belief that the set of discriminators is based largely on the specific application, and hence the set would change somewhat in composition from the one depicted above for certain applications. As an example, the use of composites as bearing materials or in reciprocating parts automatically adds wear resistance as an important discriminator. Figure 24 depicts the level of detail possible under a specific discriminator, in this case - microstructure. It is fairly well established that a composites manufacturing process can be related to its microstructure through the attributes of fiber dimension (length and diameter), fiber volume fraction, orientation flexibility and tailorability, and part-to-part repeatability. Although not shown in the example screen, it has to be mentioned that it is attributes such as microstructural flexibility that set a process such as Resin Transfer Molding (RTM) apart from the others, due to the immense opportunity for local tailoring of the microstructure. The availability of such data makes it easier for the designer to select from different options, keeping not only design, but also manufacturing, production, and economic criteria in mind.

It is in the facilitation of such information that a DSS is an aid to the concurrent engineering of advanced materials.



	Filament Wind.	Compress. Mold.	Pultrusion
Volume Fraction	limits: 0.4-0.75 optimum: 0.6	limits: 0.1-0.48 optimum: 0.4	limits: ≤0.75 optimum: 0.6
Fiber Length	continuous	discontinuous or random-continuous	continuous
Orientation (flexibility)	typ. limited to ±10° from winding axis (TP winding limits are less restrictive)	extreme limits. Fiber orientation is induced by flow. Difficult to design for anisotropy	Limits have been relaxed greatly in recent years. Common to pull fibers not parallel to pull axis.
Repeatability	≥5 is typical. ≤ 1°-2° is extremely difficult to obtain.	Fair	Excellent

Figure 24: Discrimination based on microstructure related quality metrics

The previous approach although helpful is often not the most efficient means of discrimination at the concept selection phase. In this phase the design team has already generated sufficient concepts, and hence needs to be able to efficiently separate concepts, rather than further develop them. The basis of the current approach is in the fact that the problem of selecting an alternative to satisfy multiple criteria is far easier if approached from a deselection - or discrimination, point of view. The object of the exercise then changes from one of selecting the best alternative to one aimed at rejecting alternatives that would not meet the broad limit of specifications. The easiest method of doing this is through the cross-plotting of attributes as in Figure 25, and rejecting those concepts that do not fall within specified bounds that signify the range of the demand profile. It can clearly be seen that processes 1, 3, and 5 fall outside the acceptable bounds of the demand profile as set through parameters 1 and 2, and hence can be rejected.

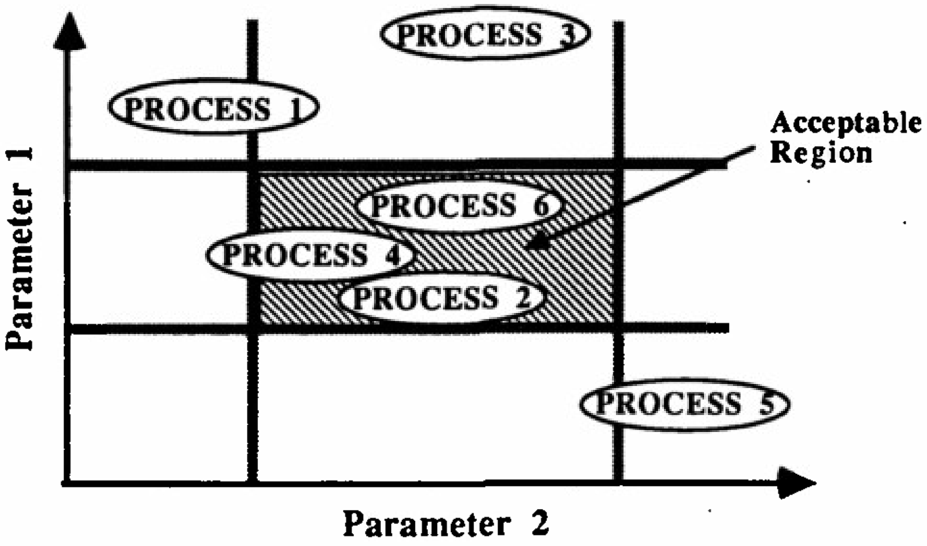


Figure 25: A schematic of the deselection process

The deletion of these reduces the further analysis to a smaller number of concepts, making it both easier to handle their selection, as well as making it cheaper in terms of time and money expended on the process.

Discrimination between close calls would then involve more detailed analysis, and in the case of actual design alternatives, it would be feasible to conduct a more thorough investigation on the remaining few concepts. In the case of structures, a full scale finite element analysis could be run on the few remaining analyses, rather than on all the concepts generated by the team, thus providing for a more efficient and economical use of time and funds. Through the use of such DSS tools it is possible to make efficient use of facilities and budgets. A key ingredient in the deselection process is the representation of knowledge such that discrimination becomes an automatic process. The choice of discriminators is thus of great importance and forms the basis for the DSS.

Figure 26 depicts an example of the discrimination of primary processes based on the metrics of shape complexity and microstructural control. Similar ideas are shown in Figure 27 for a different set of metrics, and in Figure 28 for the deselection of tooling materials for Liquid Molding.

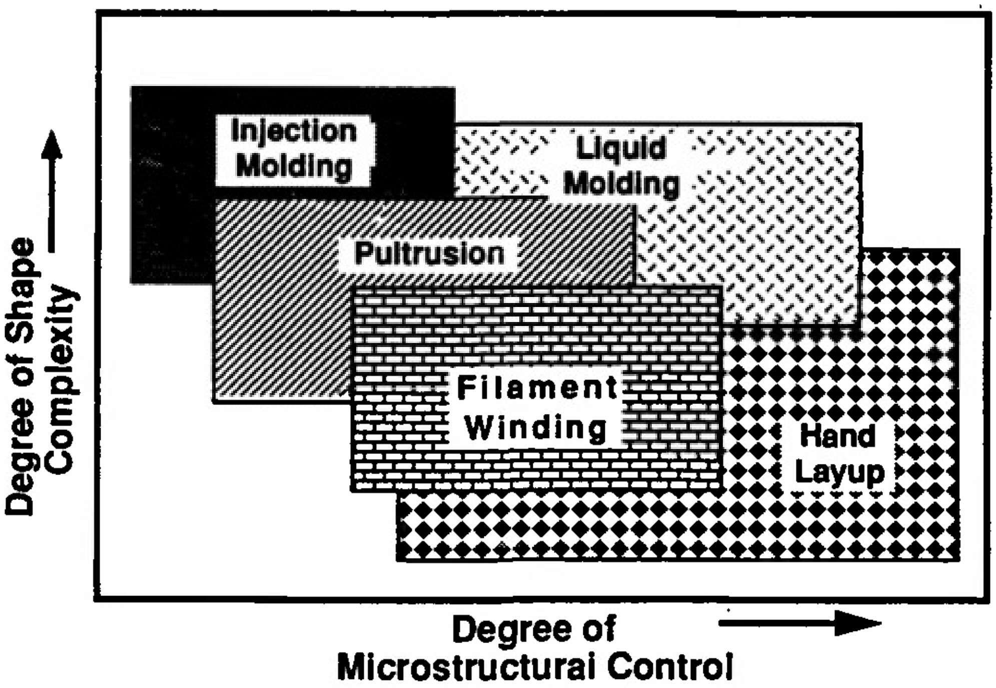


Figure 26: Primary fabrication processes

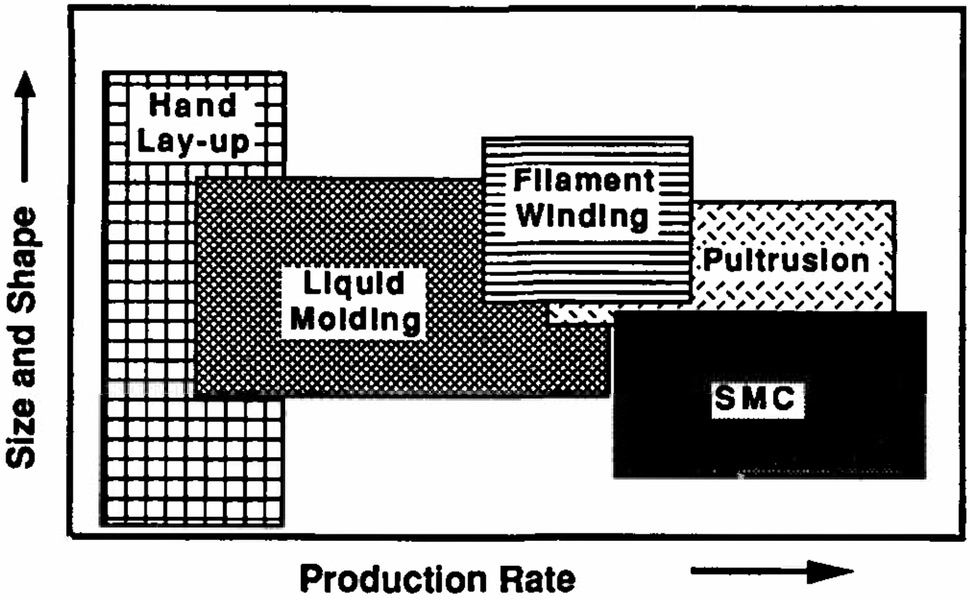


Figure 27: Deselection of primary processes based on shape/size and production rate

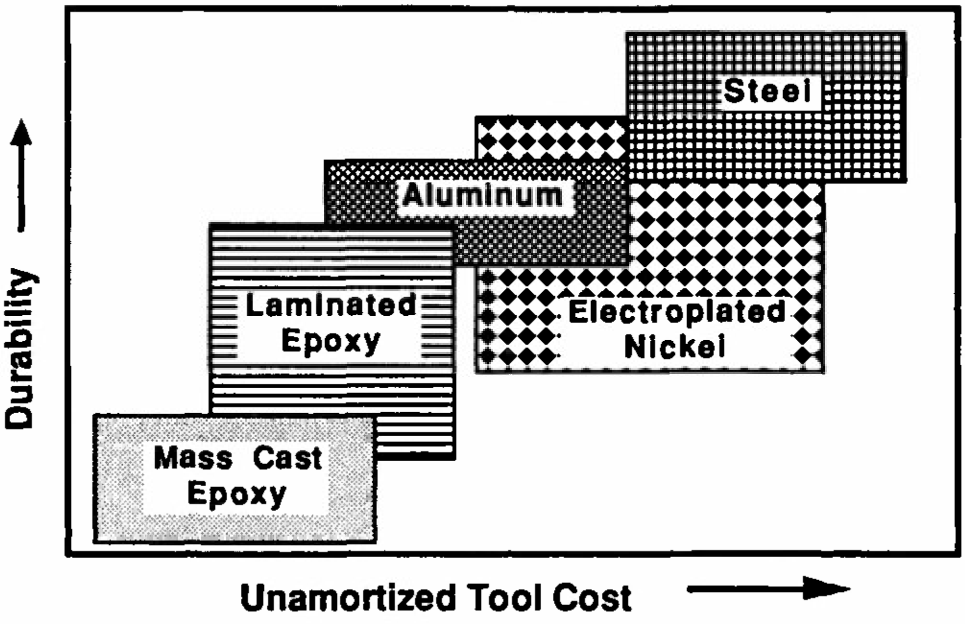


Figure 28: Deselection of tooling materials for RTM

A similar scheme is also applied to the selection (or rather of deselection) of forming processes based on the attributes of geometric complexity and size (Figure 29).

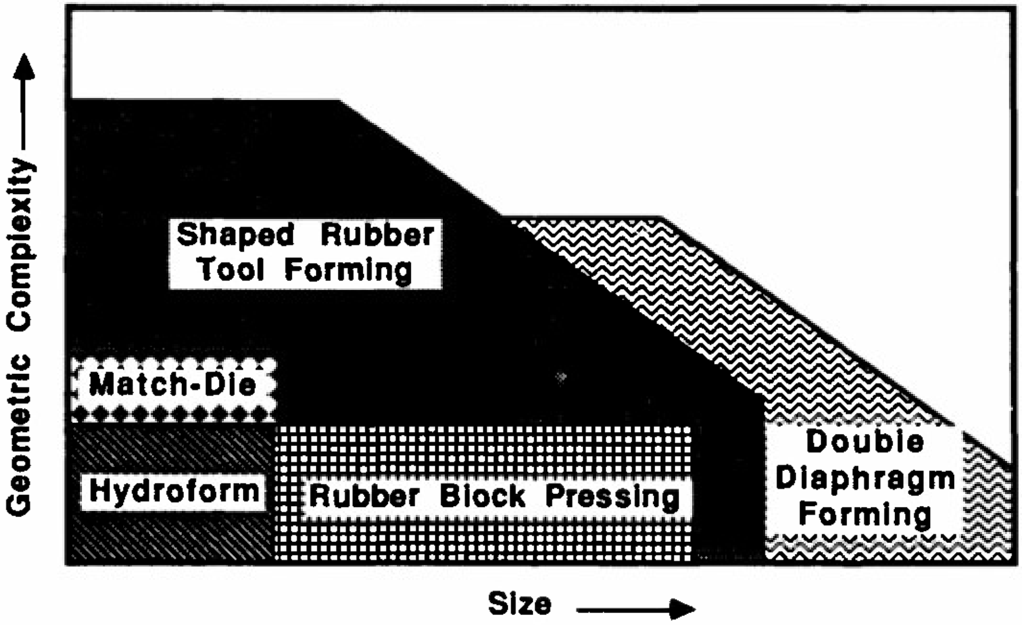


Figure 29: Relative applicability of forming processes (courtesy of Dr. A.J. Smiley)

The graphic pertains to the use of sheet-forming processes after the selection of continuous fiber reinforced thermoplastic prepreg tape (APC-2 in this case) was already made. Thus the primary material form had been selected (Figure 17), and figure 29 is merely the next step in the discrimination phase. The diagram illustrates the utility of heuristics in the selection of processes such as sheet-forming, that are still not completely understood. An indepth assessment of the applicability of each process is given in [Smiley and Schmitt, 1991]. Traditionally such data has been available in tabular form making it inherently difficult for the design team to appreciate the level of similarity or difference between two concepts. This is however, strikingly highlighted through the use of discrimination charts such as in Figures 26-29. An added feature of such a DSS is that it is possible to allow the user access to further information on a process (or concept) by "clicking" (i.e. accessing hidden information) on the concept itself as listed on the stack. This information includes a brief description of the process and could also include warnings related to the applicability and other such factors specific to the design team. Traditionally such information would have to be searched for using handbooks or the "local expert." The DSS makes such information readily accessible in a convenient format, thus serving both as a decision supporting, and educational tool. Obviously for parts of large size and medium geometric complexity double diaphragm forming would be chosen over methods such as hydroforming or rubber block pressing.

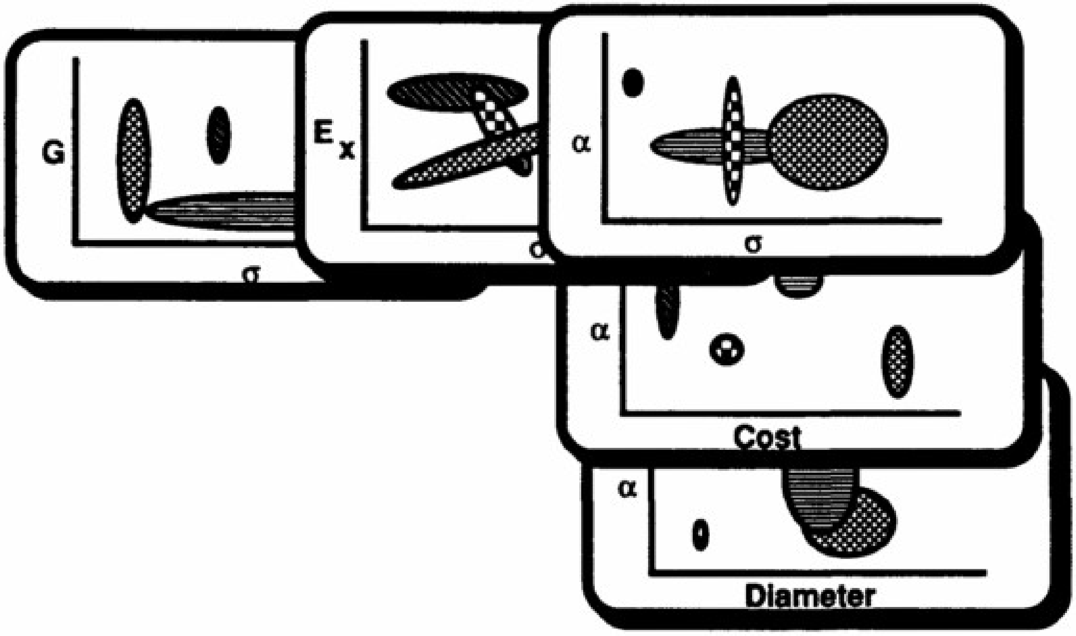


Figure 30: The complete deselection process using HyperCard® based stacks

For the efficient selection of concepts (be they related to materials or processes) it is useful to be able to view data in terms of a set of pairwise comparisons. Obviously it is of considerable interest to view the options simultaneously so as to be able to determine the optimum choices based on a number of criteria. A schematic of this is shown in Figure 30 for the selection of fibers. Criteria such as shear moduli, tensile moduli and coefficient of thermal expansion are compared to the fiber strength, whereas strength, cost and diameter can be compared in relation to each other as against the coefficient of thermal expansion. Such a scheme lends flexibility to the materials-process selection stage, allowing the user or design team the luxury of simultaneously reviewing the performance of a number of options based on a variety of criteria.

Figures 31-34 present the cross-plotting of processes based on five selection criteria. In all these the letters TS stand for "thermoset", and TP for "thermoplastic". The criteria of tooling cost, part complexity, repeatability and level of waste are plotted against a common metric - production rate.

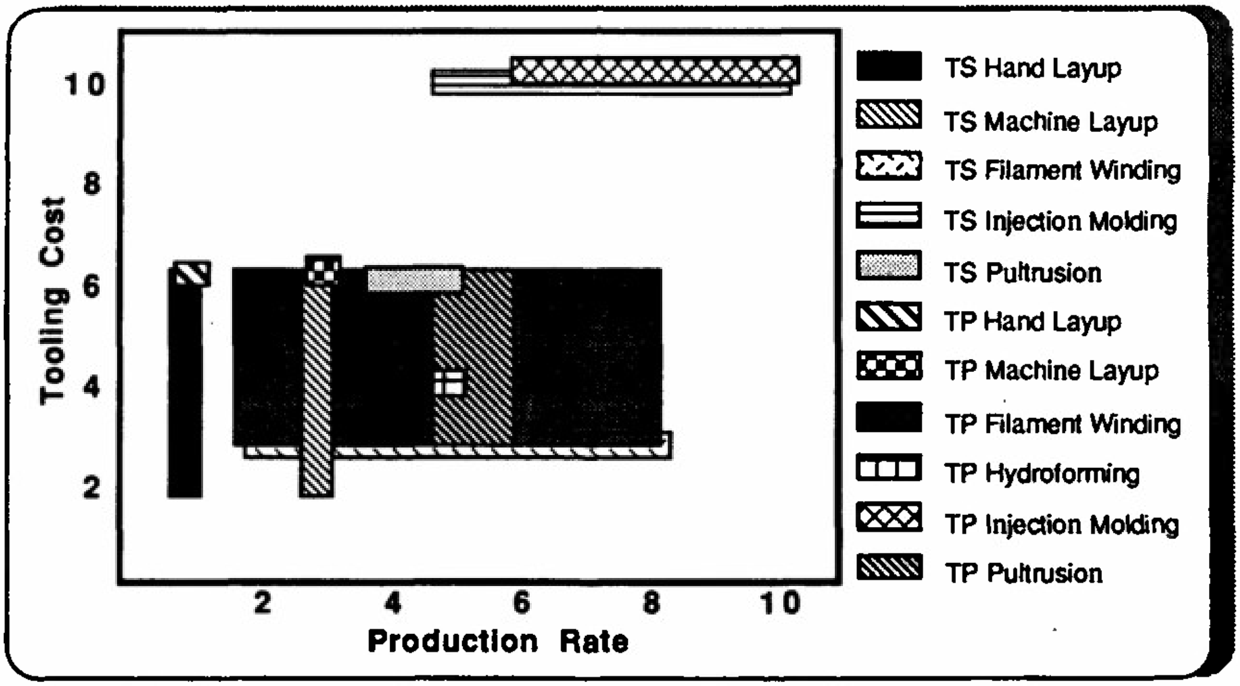


Figure 31: Deselection of processes based on tooling costs and production rate

These are among the metrics which are not as readily quantifiable as others such as cycle time and pressure. However, they are often better discriminators. They also are primarily used as production and/or economic criteria on the basis of which a specific process would be selected. Obviously, the rankings are heuristic and based on judgement, but they do serve as guides for the engineer or design team. For the basis of comparison the processes were ranked on a 1-10 scale with 1 subjectively being the lowest and 10 the highest or best. As an example, under tooling (Figure 31), 1 would represent no need for tooling, whereas 10 would represent the equivalent cost of a tool for injection molding.

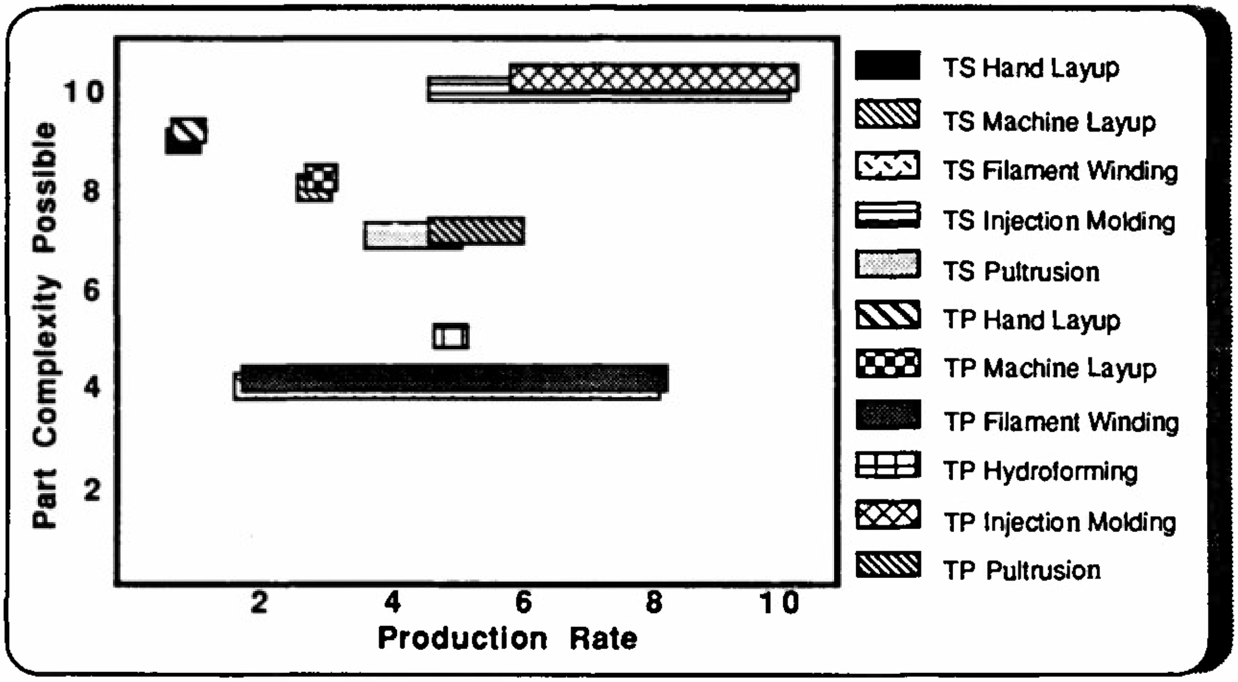


Figure 32: Deselection of processes based on part complexity and production rate

Similarly a level of 1 in Figure 32 represents the complexity of a flat plate, whereas 10 would be representative of a integrated three dimensional structure. The level of waste reuse is an indicator of the efficiency of usage of the material systems in a specific process. A level of 10 represents a process in which almost all waste is reusable, whereas a level 1 process would be one wherein the product quality would be such that rework and/or a high rejection rate is a normal fear.

Based on these four figures, it is possible for the design team to arrive at conclusions in regard to deselecting (i.e., dropping from consideration) a number of non-viable processes very early in the design stage. This not only saves time and money, but also allows the designer (or design team) to focus on the really important and viable concepts. The visual process also provides a tool whereby it is possible to justify why a concept was dropped or to specify the lack of performance based on specific criteria by the rejected concept.

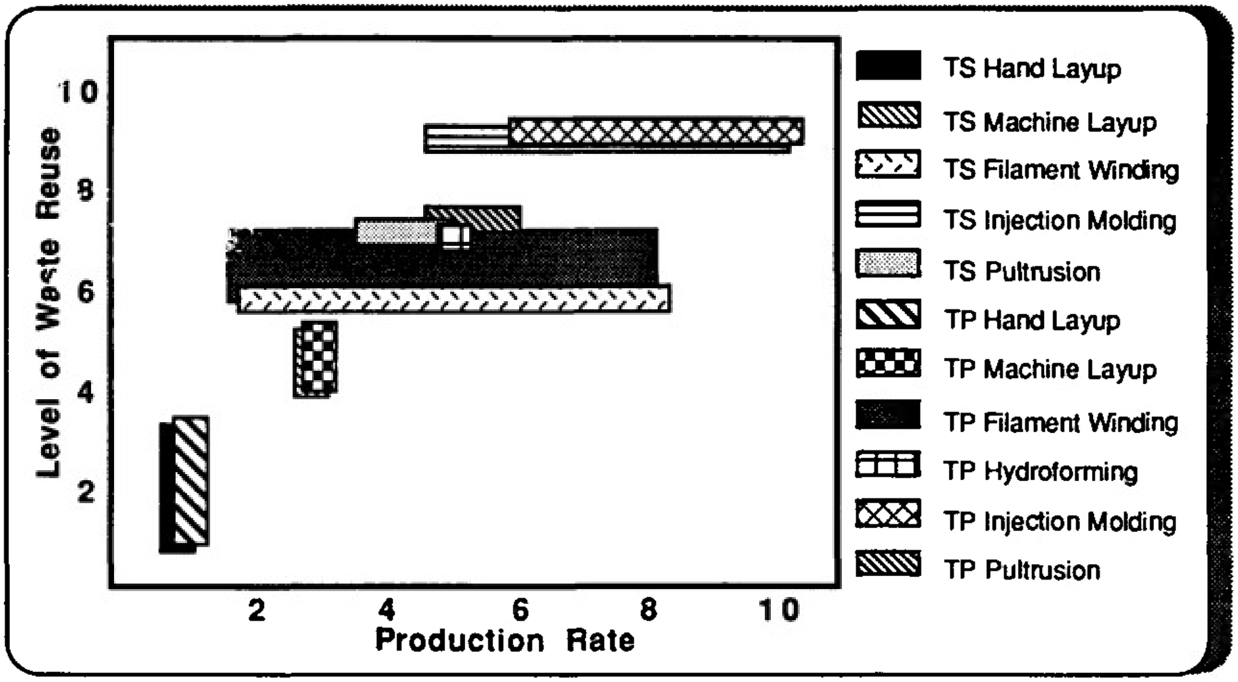


Figure 33: Deselection of processes based on level of waste reuse and production rate

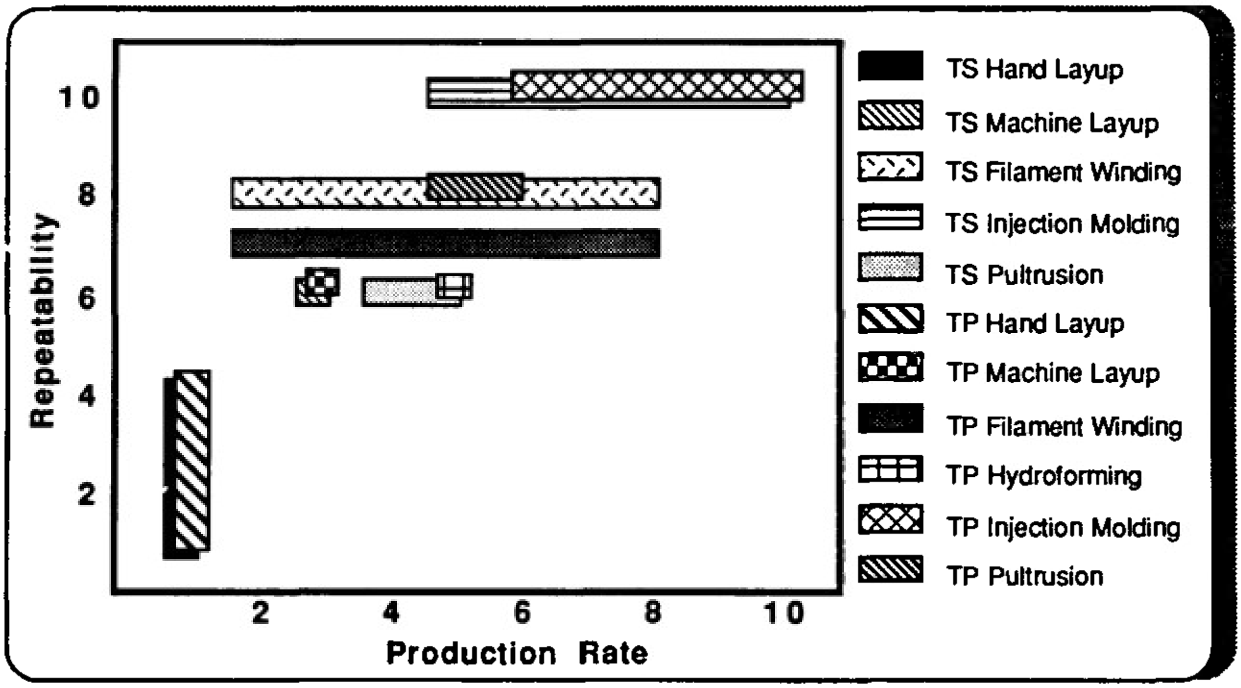


Figure 34: Deselection of processes based on process repeatability and production rate

This is not possible in a traditional computer based materials and/or process selection scheme where deselection is done on the basis on preset and very rigid bounds. This has often led to the exclusion of a concept merely on the basis of its having failed the bound test by a fraction of a percent, even though its performance with regard to other key selection criteria was exemplary.

6. CASE STUDIES

6.1 UTILITY OF THE COMPOSITES MANUFACTURING GUIDE

The utility of the CMG can perhaps best be described by showing its application to real-world composites design projects. The following examples show how the CMG is applied to several projects of interest to the U.S. Army Missile Command (MICOM). These examples are designed to show how a user (or group of users) might use the CMG in the conceptual stages of a composites development project. The CMG, like any Hypercard application, is best explored in real time on the computer. It is difficult to capture the flavor of a session with the CMG on paper. Nevertheless, the following examples are presented to show the utility of the system.

6.1a TGSM Wingform

The TGSM (terminally guided submunition) wingform is a wing-like device that folds into a small package for storage within a larger delivery vehicle. When the TGSM is deployed, the wingforms (four per TGSM) deploy into their open, wing-like position, allowing the TGSM to fly. The presence of four separate wingforms per TGSM results in a large number of individual components and manufacturing operations for each TGSM. The TGSM project is currently in an advanced state of development. A prototype exists that has been tested and found to perform its mission very well. Thus, any modifications, including the use of composite materials for any of the components, would have to preserve those performance characteristics. Incentives to modify the system (i.e., to consider the use of composites) include the potential to save weight, the potential to reduce fabrication costs, and the potential to improve performance.

The system as currently designed includes a set of stamped, bent, and machined aluminum leading edges and lamellae for each TGSM wingform. When the TGSM is stored, the leading edges and lamellae are packaged inside a hollow strake, which is machined from aluminum. The TGSM system as it currently exists performs its mission well. A number of concepts, however, might be employed to improve the system, in terms of system weight, costs, schedule, performance, and packaging. Perhaps the simplest concept involving composites would be to simply substitute composites into the current system without a radical redesign. Because of the nature of composites, some redesign would be necessary both to take advantage of the special properties of composites and their unique manufacturing methods, but the basic TGSM system (i.e., four wingforms that fold into a strake) would be left as intact as possible. Other more radical concepts might include redesigns that would cut the number of wingforms from four to three or two, changing the configuration of the wingforms, changing from a folding lamellar wingform to a fabric or inflatable fabric wingform, and so on. The point is that the simple composites concept is just one possible way to improve the existing system. This provides a good example of the utility of the CMG.

At this point, the CMG may be brought into play to aid in the decision process for the simple composites concept described above. The following component parts of the TGSM are considered: the strake into which the wingforms fold, the leading edge of the wingform, the lamellae that make up the remainder of the wingform, and the fin that acts as a stabilizer for the TGSM behind the wingform. Some of these parts are shown schematically below in Figure 35. The leading edge of the wingform is on the order of one foot long; each of the lamellae is progressively shorter. The maximum wall thickness of each of these parts is less than 1/2 inch.

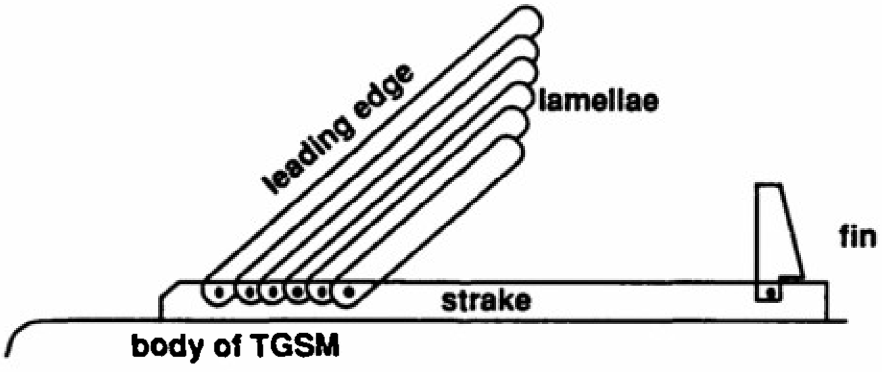
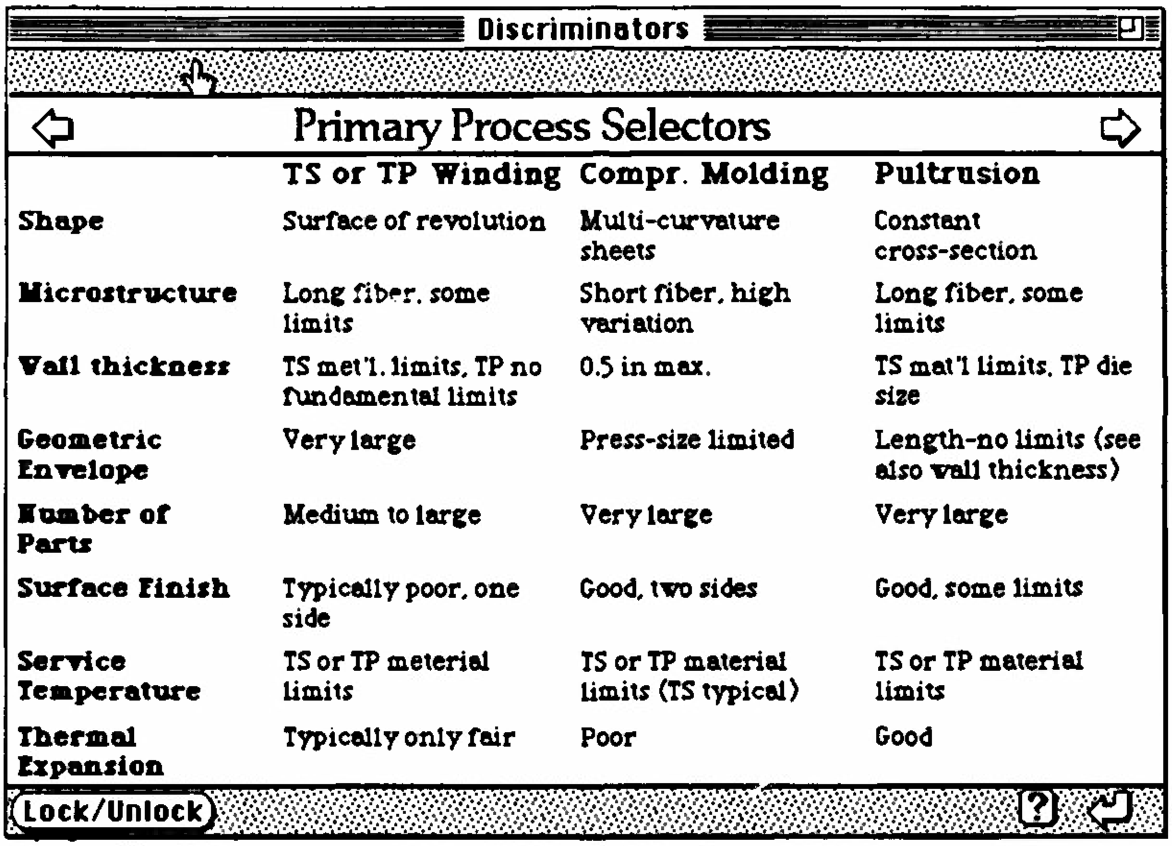


Figure 35 - Schematic of several components of TGSM wingform

The primary manufacturing processes available to the composites design team are shown in the Manufacturing Stages stack of the CGM within the "Primary Process" stage. Clicking on the **Primary Process** button leads to the Discriminators stack. Specifically, the user is shown a matrix wherein each primary process is considered in terms of a number of discriminators, or parameters that allow the deselection of various alternatives in favor of others. In many cases, "top level" information of this type is sufficient to eliminate from consideration several options. For example, in the case of the leading edge and lamellae of the TGSM wingform, it can be seen (Figure 36) that winding processes are an unlikely fit, since the parts in question are not surfaces of revolution.



Primary Process Selectors

	TS or TP Winding	Compr. Molding	Pultrusion
Shape	Surface of revolution	Multi-curvature sheets	Constant cross-section
Microstructure	Long fiber, some limits	Short fiber, high variation	Long fiber, some limits
Wall thickness	TS met'l. limits, TP no fundamental limits	0.5 in max.	TS mat'l limits, TP die size
Geometric Envelope	Very large	Press-size limited	Length-no limits (see also wall thickness)
Number of Parts	Medium to large	Very large	Very large
Surface Finish	Typically poor, one side	Good, two sides	Good, some limits
Service Temperature	TS or TP meterial limits	TS or TP material limits (TS typical)	TS or TP material limits
Thermal Expansion	Typically only fair	Poor	Good

Figure 36 - Sample card from "Discriminators" stack showing matrix of three processes and eight discriminators

Important information about other processes that cannot be so easily deselected is also available. For example, the user may note that in terms of many of the discriminators, three primary processes: RTM, injection molding, and hand layup appear to be feasible. The "number of parts" parameter is one case in which the user can use the CMG to discriminate among these processes. By clicking on **Number of Parts** in the left hand column (Figure 36), the user is shown tabular and graphical comparisons of the economic production limits of the various primary processes (Figure 37). The user must then consider the application itself in terms of the anticipated production run. In this case, a short run would tend to favor the labor intensive hand layup process (HL in Figure 37), while a longer run would favor the semi-automated RTM process. A very large run would favor the highly automated injection molding process (IM in Figure 37). If it is decided that annual production rates are large enough to deselect the hand layup process, the user may continue to use the CMG to dig further into the RTM and injection molding options.

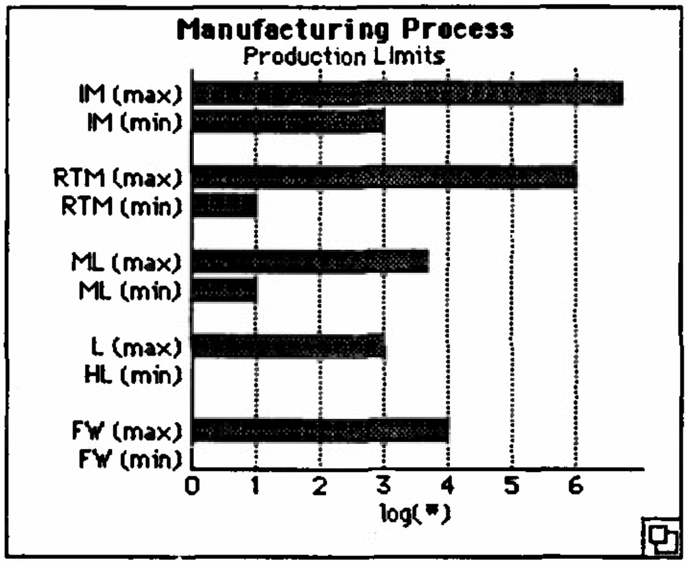
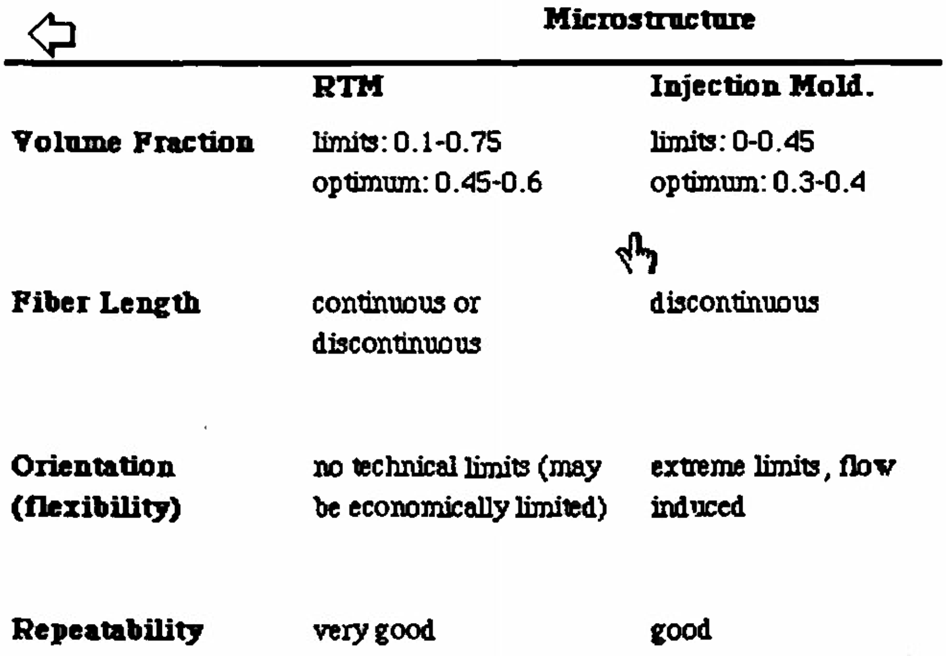


Figure 37 - Composites Primary Processes versus economic production limits (shown on log scale of annual production in number of parts)

To this end there are of course other parameters that discriminate among these processes. The RTM and injection molding processes vary greatly in terms of their ability to produce "high performance" material properties. By clicking on the **Microstructure** button, shown in the left hand column of Figure 36, the user is given more detailed information about the fiber volume fractions, lengths, and orientations that each process can produce, as well as information on the part-to-part repeatability of the process. Figure 38 shows an example of this data for the injection molding and RTM processes. (As with the number of parts information, this data may also be viewed graphically.) It can be seen that the injection molding process is limited to discontinuous fibers and to fiber volume fractions of 0.45 maximum. The RTM process is flexible enough to accommodate either continuous or discontinuous fibers and can produce parts with very high fiber volume fractions. Thus, the two processes may be discriminated by their microstructural abilities. The user must once again consider the application, and whether the microstructural limitations of injection molding can be overcome through innovative part design. This latter consideration is currently beyond the scope of the CMDG. As the CMDG continues to evolve, these kinds of design/manufacturing tradeoffs will be addressed in more and more detail.



Microstructure

	RTM	**Injection Mold.**
Volume Fraction	limits: 0.1-0.75 optimum: 0.45-0.6	limits: 0-0.45 optimum: 0.3-0.4
Fiber Length	continuous or discontinuous	discontinuous
Orientation (flexibility)	no technical limits (may be economically limited)	extreme limits, flow induced
Repeatability	very good	good

Figure 38: Microstructure information on RTM and Injection Molding processes

The CMDG as described herein does not perform reasoning (artificial intelligence) on the various stages, options within stages, or discriminators among options. It presents the pertinent data and leaves the user to draw conclusions from that data. It is expected that with the use of the current methodology and information in the CDMG, a further extension in the form of a design assistant would be the next plausible step to be undertaken. This will enable the reasoning to be conducted electronically on the basis of available information, thereby giving the team not only information, but also options for the design itself.

6.1b RNT-5 Turbojet Engine

The RNT-5 is an unmanned jet propelled flying vehicle. The turbojet engine of the RNT-5 contains several components that could be considered for composites redesign. These include the two engine inlet ducts, the airframe body, and the internal rails on which various internal components are slide-mounted. These components are shown schematically in Figure 39.

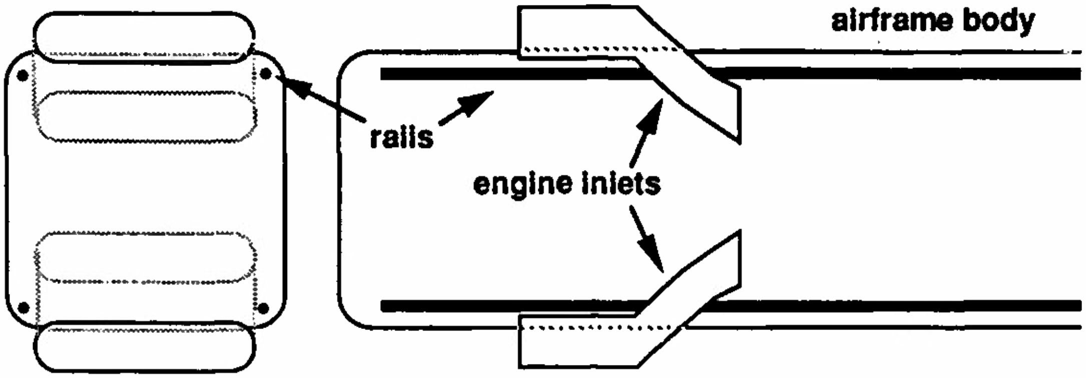
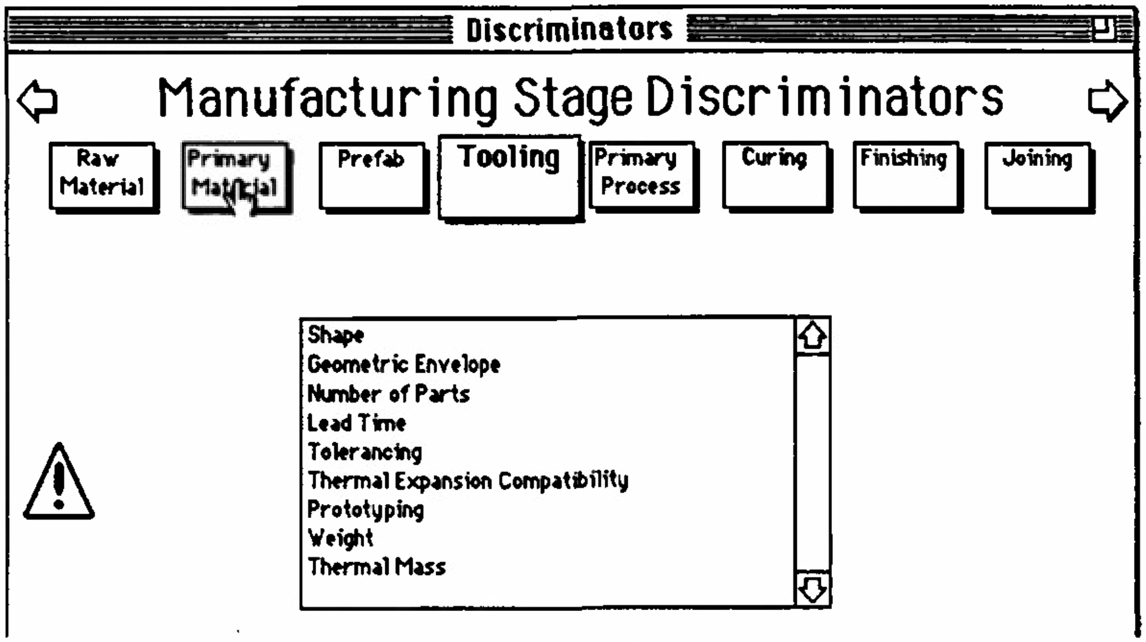


Figure 39 - Schematic of engine inlets, airframe body, and rails of RNT-5

The two identical engine inlets are parts whose complex shape probably precludes any consideration of, for example, winding or pultrusion processes. Quick consultation with the CMG reveals that the only two processes likely to produce such a complex "casting" type shape are RTM and injection molding. Assuming that the user determines that injection molding is unlikely to deliver the necessary performance, a more thorough examination of the RTM option might be considered. The Discriminators stack could be used to determine the discriminators at each stage (up to this point in this and the previous example, only the primary process stage has been considered). For example, to determine the discriminators in the tooling stage of manufacturing, the user would go to the tooling card in the manufacturing process stage, and click on **Tooling** above the options field. Figure 40 shows the top portion of the destination card in the discriminators stack. Note that the list of discriminators for the tooling stage is different from the list shown in Figure 36 for the primary process stage. In similar fashion to the process described for the TGSM example for primary processes, the user can explore the options and discriminators for the tooling stage of manufacture. For the current example, the user might wish to determine which tooling processes are compatible with RTM, what subset of those processes should be considered for prototyping as opposed to production, and which suppliers are available to provide various types of RTM tooling. This information is readily available from the CMG.



Shape
Geometric Envelope
Number of Parts
Lead Time
Tolerancing
Thermal Expansion Compatibility
Prototyping
Weight
Thermal Mass

Figure 40 - Discriminators for the tooling stage of composites manufacture

The CMG could likewise be consulted regarding the airframe body and rails. Options and discriminators for primary processes, tooling and other stages are readily determined, guiding the design team quickly towards detailed consideration of the vital few manufacturing process concepts that it should be considering in greater detail.

6.2 QUALITY CONTROL

Although it is fairly easy for the design team using the CMDG as outlined in the examples above, to reach a decision as to which material system, configuration and/or process is best suited for a specific task, there is no way to assure that quality would be built into the design. Also, since every manufacturing process is largely dependent on the actual equipment used, there is a need to verify that a chosen option is viable under the specific conditions prevalent at a site. The following example describes the use of the TAGUCHI method for the determination of critical parameters after the CMDG was used to determine that RTM would be the most appropriate process for the customers requirement. The CMDG was also used to determine that the use of flat plaques, rather than other more complex shapes would be sufficient to get the required information efficiently using experimental means.

6.2a USE OF TAGUCHI METHODS

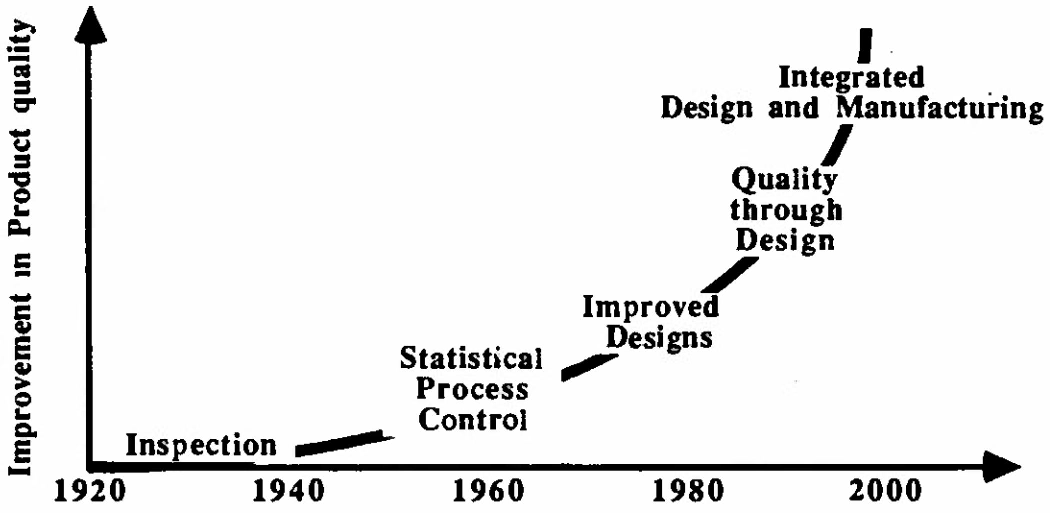


Figure 41: The evolution of quality control

Now, more than ever before, processing costs and problems of repeatability can stall new composite programs right at the profit line. Marginal improvements in the control of composites manufacturing processes, although useful in the short term, will not provide the needed levels of quality, reliability or economy of production. Figure 41 depicts the shift in approaches used to ensure product quality as a function of time. Taguchi methods belong to the class of approaches that attempt to ensure quality through design, in this case through the identification and control of critical variables (or noises) that cause deviations to occur in the process/product quality.

Lately, great importance has been placed on building quality control into the manufacturing operation. This has led to the emergence of the developing field of intelligent manufacturing for composites. The aim of intelligent manufacturing is to use immediate feedback to achieve the direct control of product characteristics. This, however, requires that a comprehensive set of models are available so that each step of materials transformation during processing is understood and hence can be controlled through the use of appropriate control systems. There is, however, an immediate need for methodologies and approaches that would allow for the identification of the process window within which the process is largely insensitive to local variations in raw material quality, process settings, and the environment. Traditionally, process R&D has been conducted on a trial and error basis, leading to a considerable lag time and expenditure in defining efficient process windows, and/or improving the robustness of the processes through the identification of critical process parameters. Whereas it is often possible to speed up this activity for mature technologies and processes for which a considerable knowledge base exists, it is close to impossible for emerging technologies such as RTM.

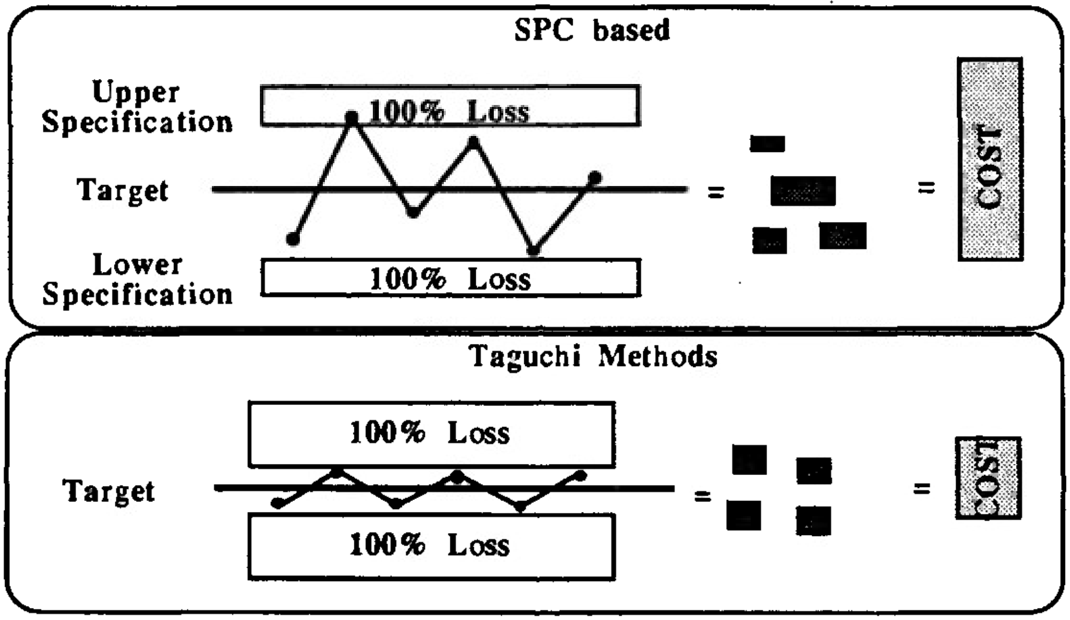


Figure 42: A comparison of methodologies

Taguchi methods, developed by Dr. Genichi Taguchi, refer to techniques of quality engineering that embody both statistical process control (SPC) and new quality related management techniques. Most of the attention and discussion on Taguchi methods has been focussed on the statistical aspects of the procedure, it is the conceptual framework of a methodology for quality improvement and process robustness that needs to be emphasized. The entire concept can be described in terms of two basic ideas:

1) Quality should be measured by the deviation from a specified target value, rather than by conformance to preset tolerance limits, and

2) Quality cannot be ensured through inspection and rework, but must be built in through the appropriate design of the process and product.

The first concept underlines the basic difference between Taguchi methods and statistical process control (SPC) methodology. Whereas SPC methods emphasize the attainment of an attribute within a tolerance range and are used to check product/process quality, Taguchi methods emphasize the attainment of the specified target value and the elimination of variation (Figure 42). In conjunction with the second concept, this assumes great significance for composites manufacturing since Taguchi methods emphasize that control factors must be optimized to make them insensitive to manufacturing transients through design, rather than by trial and error. SPC allows for faults and defects to be eliminated (if detected) after manufacture, whereas what is really needed is a methodology that prevents their occurrence - in this case, the methodology is the use of Taguchi methods. This then presents a powerful tool for composites processing within which there is an inherent variability due to raw material quality and/or noise in the process environment itself. Thickness variation in prepreg, local areas of poorly consolidated material in thermoplastic filament winding, and areas of poor wet-out in resin-transfer molding are just examples of material and process induced sensitivity. Within the focus of this paper we shall concentrate on the application to the RTM process.

Through the proper design of a system, the process can be made insensitive to variations, thus avoiding the costly eventualities of rejection and/or rework. In order to determine and subsequently, minimize the effect of factors that cause variation, the design cycle is divided into three phases of System Design, Parameter Design, and Tolerance Design, as depicted in Figure 43.

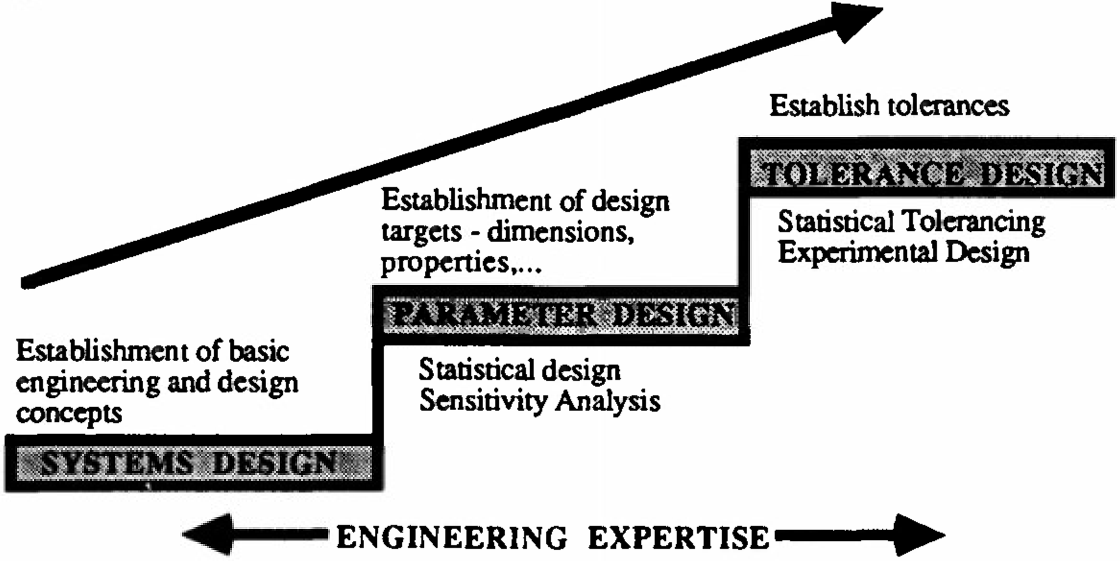


Figure 43: Stages in the design cycle

It is the second phase that we are considering in this investigation. This is done through intelligent and effective use of experimental design and statistical techniques with the intent of identifying factors causing variation in output characteristics, and then designing the process in a way such that these are insensitive to variation. Taguchi proposed new methods of using statistically planned experiments [Taguchi, 1987] by classifying variables into design parameters and noise. The design parameters are those whose levels can be chosen in advance and controlled through the process. Noise comprises those variables that cause output characteristics to deviate from their targets.

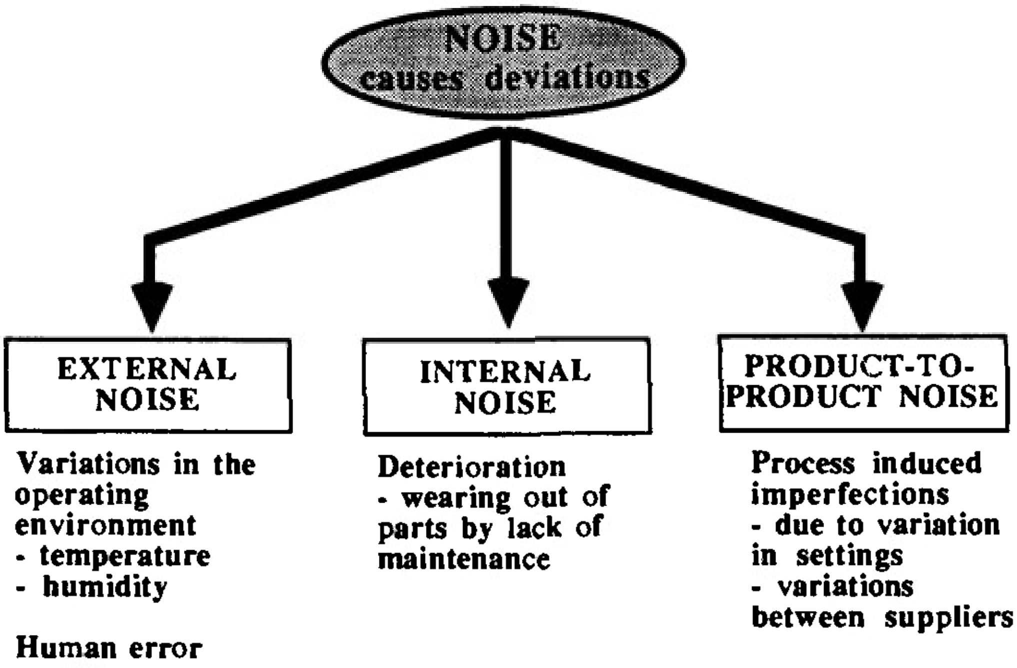


Figure 44: Types of noise

Thus anything that could conceivably cause a quality characteristic to deviate from its target is classified as noise. Variation in yarn bundle diameters, local variation in binder content, minor changes in stroke characteristics of the injection equipment could thus be sources of noise within the RTM process. The objective of Taguchi methods is not the control of nuisance variables, but in making the process insensitive to them. The design variables are arranged in a matrix for experimental design. This is often termed as the "inner array." The noise factors form the "outer array" and combinations of the two matrices define a complete Taguchi test. For the purposes of the current investigation, only the design matrix (or inner array) is used. It must be stressed that one of the primary motivations for using the Taguchi arrays is to concentrate on the effects of variables, and to neglect second and third order interactions between them. The interested reader is referred to the excellent articles by Kacker [1986], Taguchi and Clausing [1990] and Barker [1986] for further details on the philosophy and methodology associated with this approach.

The RTM Process

Resin Transfer Molding (RTM) is a versatile and efficient process that is gaining popularity in the automotive, aerospace, and sporting goods industries due to its potential for forming near net shape parts with highly tailorable reinforcement, in a fairly repeatable manner, at a low capital investment in comparison with other competing processes such as automated layup and filament winding. Conceptually, RTM is a fairly simple process. It begins with the reinforcement in the form of dry (unimpregnated) fibers/roving being oriented and shaped into a preform, that acts as a skeleton of the actual part. The preform is then loaded into a tool. After closure of the tool, a low viscosity, reactive resin system is injected, which impregnates the preform prior to gelation. Next, the entire part is cured, and once it has attained sufficient green strength, is removed from the tool. Although the basic process has been in existence for decades, it is only of late that there has been an interest in it from the advanced composites community, raising a clamor for a science base and understanding of the process itself. It is still a very immature technology, and is hence an ideal candidate for the use of the Taguchi method in the identification of control variables, and the optimization of the process window and parameters associated with ensuring robustness of the process.

The variables associated with the quality of the final part range from those related to the preform and resin, to those related to the tool itself, as well as to the equipment and methods used in processing. The variables associated with the preform reinforcement include the fiber/roving diameter, fabric architecture (Continuous strand mat, plain weave, unidirectional, multi-axial etc.), binder type and amount, sizing, and density. There is considerable evidence that reinforcement material manufactured by different companies, even though rated as being the same in all respects behave very differently in areas such as wet-out, compatability, and mechanical properties [Johnson and Houston, 1990]. The tool itself is a source of considerable variation in part quality through factors such as tool surface finish, sealing mechanisms, venting and gating arrangements, and heating and cooling arrangements. It should however be remembered that the tool itself forms a significant fraction of the cost involved with the use of the RTM process, and hence most of these variables are design variables, rather than process variables, since they have to be considered primarily during tool fabrication. The resin system itself can be the source of a number of variables related to viscosity, wet-out and cure. The formulation of the system is a critical stage and minor variations in the ratios of additives and catalyst used can significantly influence the processing cycle most notably through the gel time and degree of cure. The process of injection as well as the injection pressure used are very important as they can have a deleterious effect on performance if the procedure results in considerable wash or actual damage to the preform structure and/or material itself.

Experimental details

Based on prior experience of the investigators as well as on the potential for control of parameters, a list of seven material and process related variables were chosen at two levels each for the current investigation as listed in Table 2.

Factor	Level 1	Level 2
Preform material type	A	B
Number of Layers	3	5
Stroke Length (inches)	3.5	6
Gating arrangement	Center	Corner
Injection Pressure (psi)	40	75
Shot type	Single	Continuous
Tool Temperature (°F)	Room (70°)	120°

TABLE 2: Control factors and their levels

In order to include effects due to material variability, two varieties of continuous strand mat were obtained from two different suppliers. Both materials were nominally the same being comprised of E-glass at 1.5 oz/sq. ft. However, based on measurements of binder content on another grade of the same set of materials it was found that one had as much as double the binder content. The materials will hereafter be referred to as A and B. Since the effects of compressibility and permeability are coupled, it was also decided to use two levels of fiber volume fraction, nominally taken to be represented through the use of 3 or 5 layers of reinforcement within a space of 1/8 inch. A vinyl-ester (Derakane 411-C50) resin system was used for this experiment and was formulated as 2 parts of Trigonox R-239A and 0.5 parts of NL51P (6% Co) to 100 parts of the resin. The typical gel time for this system was 20 minutes at 20°C, and it possessed a viscosity of approximately 100 cps at 25°C (77°F). Injection of the resin system was achieved through the use of Liquid Control injection equipment with a positive displacement pump driven via a pneumatic cylinder arrangement. Use of this allowed for control over injection pressure as well as the amount of resin dispensed during one stroke of the piston. Two pressures, 40 and 75 psi, were used with this equipment. The use of a variable related to the mode of injection used with the equipment (single shot versus continuous) was included to investigate the effect of machine and human elements in the process. (It was subsequently however concluded that for the mechanical properties determined this had a negligible effect). The shot size is controlled by the stroke length of the pistons used in the pump. The length of the stroke determines the forward movement of the piston and hence the dispensed volume of the resin system. It is inherently obvious that a shorter stroke length would result in smaller quantities of resin being injected into the tool, thereby needing a larger number of strokes to fill the tool. An important factor linked to the choice of the stroke length is related to the pulsating form of injection that is typical of such injection equipment. The use of a shorter stroke results in shorter cycles and thus a smaller overall pressure drop between the beginning of one stroke and the next as well as a shorter time span associated with this differential. Two stroke lengths, 3.5 inches and 6 inches, were selected for this experiment. The latter represents the maximum possible stroke length for the specific injection equipment used, whereas the former was chosen as being at the lower end of one of the specific limits of injection pressure (40 psi) already chosen. Injection was done through a central sprue or through one corner as depicted schematically in Figure 45.

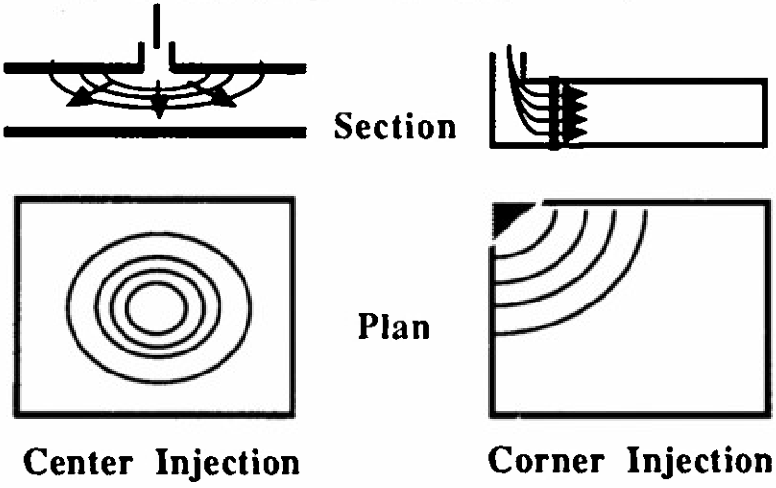


Figure 45: Schematic of the gating arrangements used

Two values of tool temperature, 70°F (nominally taken to represent a controlled room temperature), and 120°F were selected. Care was taken to ensure that the temperature stabilized on both tool halves at the required level before use. The temperature settings were accurate to within ±3°F.

The chosen parameters were arranged in matrix form using an L_8 Taguchi array, that allowed the investigation of the 7 factors through eight experiments. The actual settings are shown in Table 3, which the discerning reader will recognize as being identical to the one used by Taguchi in the Ina Seito tile experiment [Taguchi, 1986].

Expt. No.	CoSM Type	Number of Layers	Pump Stroke Length (inches)	Gating Type	Pressure (psi)	Shot Type	Tool Temp (°F)
1	A	3	3.5	Center	40	Single	70
2	A	3	3.5	Corner	75	Cont.	120
3	A	5	6	Center	40	Cont.	120
4	A	5	6	Corner	75	Single	70
5	B	3	6	Center	75	Single	120
6	B	3	6	Corner	40	Cont.	70
7	B	5	3.5	Center	75	Cont.	70
8	B	5	3.5	Corner	40	Single	120

TABLE 3: The Orthogonal array design for the actual experiment

It is to be noted that the array is such that the columns are orthogonal, each of the possible combinations of variable levels occurring twice in any given pair of columns. Moldings were produced in the form of flat plaques 9" x 9" in size and 1/8" in thickness. Once molded the plaques were post cured at 200°F for 3 hours as per suggestion from the resin supplier. The plaques were then cut using a diamond edged blade to form coupons for open hole tension, and flexure tests.

Results and discussion

The open-hole tension specimens used were 1" wide with a 0.25" hole drilled in the center. Specimens were untabbed, and failed uniformly from the hole. A cross head speed of 0.05 in/min was used for all specimens tested in tension. Half inch wide specimens were used for 4-point flexure testing following the set-up given in ASTM D 790-86. The support span was 4 inches with the load span being 2 inches, loaded at a uniform cross-head speed of 0.2 in/min. The results of the analysis of variance (ANOVA) conducted is shown in Table 4.

Factor	**Open Hole Tension**		**4 point Flexure**	
	% of Variation	Choice	% of Variation	Choice
Material	47.65	A	2.00	B
No. of layers	18.16	5.0	4.00	3.0
Stroke length (in.)	2.01	3.5	77.00	3.5
Gating	11.45	Center	4.00	Corner
Inj. Pressure (psi)	16.39	40.0	4.00	70.0
Shot type	0.52	Continuous	3.00	Single
Tool Temp. (°F)	3.82	120	5.00	Room

TABLE 4: Results of the ANOVA

For the open hole tension tests, it can easily be seen that the major contributors to the variation in results are the preform material type, the number of layers used, the type of gating, and the injection pressure. However, from the flexure test results the stroke length appears to be the major contributor, far overshadowing all other factors. In order to understand this phenomenon, it is necessary to consider the details of the operation of the pumps used in the injection equipment. The pumps are such that at the onset of each stroke the injection pressure increases and then drops at the end of the stroke whilst the piston retracts to fill the head again. With a long length of stroke the pressure differential between the different stages of the stroke itself is pronounced, whereas with the shorter stroke length pressure is more uniform. This is seen to have a major effect on the performance of parts as was determined through the current set of experiments. Corroborating evidence of such effects has also been noticed, although reportedly not studied, by the manufacturer of the injection equipment. Although most of the RTM injection equipment available today is rated as belonging to the "positive-displacement" type, this is not entirely true. Confirmatory tests were run using the "choice" settings from the ANOVA. It should be remembered that two different sets of parameters were identified as being optimum for the open hole tension and flexure tests, thereby signifying that the process and material parameters affecting both types of mechanical behavior are different. The confirmation experiment for tension gave results that were higher than those from trials 1, 2 and 4 and at about the same average value as those from trial 3. It may be noted that the specimens from trial 3 showed extremely bad wet-out, and the high tensile strength for this specimen is considered to be mainly due to the tensile strength of the glass fibers themselves rather than that of the composite. It may be noticed that specimens from both trials 3 and 4 were fabricated using 5 layers of the continuous strand mat, which was the same number as that used in the preform for the confirmation experiment. The average strength from the confirmation experiment was seen to be 35.6% greater than that from trial 4, and only 5% lower than that from trial 3 (which as mentioned before was very poorly wet-out). For the flexure tests, however, the confirmation experiment (3 layers) gave results higher than those of trials 5 and 6 (also 3 layers), but lower than those for specimens with 5 layers (trials 7 and 8). A number of reasons could be hypothesized for this including the effect due to fiber volume content, and the fact that although the stroke length setting was established as 3.5 inches, it actually varied during the confirmation experiment from 3.5 to 6 inches. Since the ANOVA indicated that the stroke length itself contributed as much as 77% to the results, this malfunction could be a major contributor to the discrepancy. However, if these results are viewed after normalization for fiber volume content, the confirmatory experiment does result in a higher value of normalized flexural strength. It was also seen that the flexure results were corroborated by the results of short-beam-shear tests.

The use of the Taguchi method is seen to be very effective in determining the optimum process window for an immature technology where there does not exist a good knowledge base or experience to draw upon. In the authors' opinion it provides a valuable tool for process development and optimization. Besides the quick determination of parameters that need to be controlled during a process and the identification of others that do not really affect the product quality, the use of the Taguchi method greatly reduces the number of experiments necessary as compared with a full factorial or even a modified factorial setup.

7. SUMMARY AND CONCLUSIONS

The report describes the development and use of a methodology for the concurrent engineering of composites. Both facilitation tools and design and manufacturing guides are developed and their use explained. Case studies are shown for the use of both. The development of a decision support system for composites product development is also described. It emphasizes information and deselection criteria. The proposed methodology draws from the need for a knowledge base for composite materials and associated processing techniques [Hayes, 1990] in a format that would serve both as a decision aid for routine design, as well as a training tool for novices. The number of composites fabrication processes is very large, and the selection of the appropriate process within the design profile can provide a major problem for the design team. The use of heuristics in the form of charts can form a simplistic design support system, in that it allows the designer to quickly sieve through a number of alternatives, rejecting those that fall far out of the demand region, and then sequentially deselecting others on the basis of a ever narrowing demand profile. It is envisaged that in future the stack will be coupled with existing on-line data bases as well as with an inference engine type shell so as to be able to generate lists of allowable options at each stage of the PRP based on a predetermined range of design constraints.

The basic strategy being reinforced through this system is that of limiting conflict without skimping on quality. Simple, yet powerful tools such as discrimination charts and tables can be used to accelerate the decision making process, even in areas where decisions are highly coupled. The approach described herein favors conflict resolution through deselection, allowing multiple, simultaneous alternatives to be carried forward. The use of comparative rankings allows the decision makers to access alternatives even if the superiority of one cannot be readily quantified. The system acts as a tool towards the facilitation of concurrent engineering by ensuring that knowledge necessary for a successful product realization process is made available in the most accessible format. Through the provision of data and information as described in this paper, the appropriate design, manufacturing, and economics data is made available in a form understandable to each member of the design team. Besides being a tool for efficient design it serves to break down the walls of communication that have existed in the past between designers, manufacturing teams, and management, thus ensuring that knowledge can truly be used as a competitive edge in product development.

8. REFERENCES

Abrams, F.L., in Proceedings Detroit ReTec '87, Society of Plastic Engineers, Detroit, MI, USA, November 1987, 117.

Angehrn, A.A. and Lüthi, H-J, Interfaces, 20[6] (1990), 17.

Aoyagi, H., Uenoyama, M., Coulter, J.P. and Güçeri, S.I., unpublished results.

Ashton, J., cited in **Enabling Technologies for Unified Life-Cycle Engineering of Structural Composites.** National Materials Advisory Board, NMAB-445, National Academy Press, Washington, D.C. (1991).

Ashton, J.E., Fagan, R.L. and Cook, F.X., Manufacturing Review, 3[2], (1990), pp. 85.

Barker, T.B., Quality Progress, (December 1986), 32.

Bemowski, K., Quality Progress, (January 1991), 19.

Beris, A.N., Pillai, V. and Dhurjati, P., Center for Composite Materials, University of Delaware, unpublished results.

Brown, D.C. and Chandrasekaran, B., in **Knowledge engineering in computer-aided design**, North-Holland, Amsterdam (1985), 259.

Clark, K.B., Harvard Business Review, (November-December 1989), 94.

Cooper, R.G., IEEE Transactions on Engineering Management, EM-34[3], (August 1987), 184.

Cooper, R.G., Business Horizons (May-June 1990), 44.

Cooper, R.G. and Kleinschmidt, E.J., Journal of Product Innovation Management, 3[2], (1986), 71..

Drucker, P.F., Harvard Business Review, (May-June 1990), 94.

Edmondson, H.E. and Wheelwright, S.C., California Management Review (Summer 1989), 71.

Eisenhardt, K.M., California Management Review, (Spring 1990), 39.

Ettilie, J.E., **Taking Charge of Manufacturing**, Jossey-Bass Publishers, Inc., San Francisco (1988).

Garvin, D.A., Sloan Management Review, (Fall '84), 25.

Gero, J.S., AI Magazine (Winter 1990), 26.

Gomory, R.E., Harvard Business Review (November-December 1989), 99.

Gupta, A.K. and Wilemon, D.L., California Management Review (Winter 1990), 24.

Hauser, J.R. and Clausing, D., Harvard Business Review, (May-June 1988) 63.

Hayes, J., Reinforced Plastics (October 1990), 52.

Henshaw, J.M., A Framework and Tools for the Early Decisions in the Product Development Process, Ph.D. Dissertation, Materials Science Program, University of Delaware (1989).

Hise, R.T., O'Neal, L., McNeal, J.U. and Parasuraman, A., Journal of Product Innovation Management, 6[1], (1989), 43.

Hollins, B. and Pugh, S., **Successful Product Design**, Butterworths, London, 1990.

Johnson, C.F. and Houston, D.Q., Proceedings ASM/ESD Conference (1990), 211.

Kacker, R.N., Quality Progress (December 1986), 21.

Karbhari, V.M., Henshaw, J.M. and Wilkins, D.J., Proceedings of the 36th International SAMPE Symposium, San Diego, CA (April 1991), 705.

Karbhari, V.M. and Wilkins, D.J., Proceedings of the ASM/ESD conference, Sept. 30-Oct. 3 1991, Detroit, MI, 459.

Karbhari, V.M., Steenkamer, D.A., Wilkins, D.J. and Henshaw, J.M., published in the Proceedings of the 23rd International SAMPE technical conference, October 1991, Lake Kiamesha, NY, 313.

Katz, R.H., **Information management for engineering design**, Springer-Verlag, Berlin (1985).

Kjellqvist, J, International Journal of Materials and Product Technology, 1[1] (1986), 146.

Kliner, K.M., Proceedings of the 6th Technical Conference, American Society for Composites, October 7-9, Albany, NY, 1022.

Lange, R.D., Competencies Required for the Design and Implementation of Manufacturing Systems for Advanced Composite Structures, Ph.D. Dissertation, North Texas State University, Denton, TX (May 1986).

Lee, C.W. and Abrams, F.L., Proceedings of the 5th Japan-Us Conference on Composite Materials, Tokyo (1990), 411.

Martin, J.M., "The final piece to the puzzle," Manufacturing Engineering (September 1988).

NAE, **Improving engineering design - designing for competitive advantage**, National Academy Press, Washington, D.C. (1991).

Pryor, L.S., The Journal of Business Strategy, (Nov.-Dec. 1989), 28.

Pugh, S., **Total Design**, Addison-Wesley Publishing Company, Reading, MA (1990).

Puttre, M, Mechanical Engineering (October 1991), 81.

Ramkumar, R.L., Proceedings, SME Conference on Composites in Manufacturing, Anaheim, CA, (January 1989).

Rasdorf, W.J., Proceedings of the International Computers in Engineering Conference, ASME, Boston, MA (1985), 249.

Renner, E., Proceedings of the U.S. Army / NSF joint symposium for the technology transfer of concurrent engineering tools and methodologies, Huntsville, AL (June 1991).

Russo, I.E. and Dosher, B.A., "An information processing analysis of binary choice," Carnegie-Mellon University report (November 1976).

Slovic,P., Fischoff, B. and Lichtenstein, S., Annual Review of Psychology, 28[1] (1977), 1.

Smiley, A.J. and Schmitt, T.E., published in the Proceedings of the 23rd International SAMPE technical conference, October 1991, Lake Kiamesha, NY, 1112.

Sullivan, L.P., Quality Progress, (June 1986) 39.

Taguchi, G., **Introduction to Quality Engineering**, Unipub, Kraus International Publications, White Plains, NY, (1986).

Taguchi, G., **System of Experimental Design, Vols. 1 and 2**, Unipub, Kraus International Publications, White Plains, NY, (1987).

Taguchi, G. and Clausing, D., Harvard Business Review, (Jan.-Feb. 1990), 65.

Turtle, Q.C., in **Simultaneous Engineering**, SME, Dearborn MI (1990), 176.

Tversky, A., Psychological Review (1972), 281.

Waldron, M.B. and Waldron, K.J., NSF Engineering Design Conference (June 1989).

Waldron, M.B., in **Intelligent CAD, II**, Elsevier Science Publishers B.V., North-Holland (1990), 73.

Wilkins, D.J. and Karbhari, V.M., International Journal of Materials and Product Technology, 6 [3] (1991), 257.

Wilson, D. W., "Materials Characterization: Impediment to Expected Growth of the Composites Industry?" 1989 CCM Seminar Series, University of Delaware, Newark, DE, USA.

Winner, R.I., Pennell, J.P., Bertrand, H.E. and Slusarczuk, M.M.G., IDA report R-338, (December 1988).

Woodbury,R.F., Building and Environment, 26[1] (1991), 61.

APPENDIX 1

The Total Quality Design (TQD) Workbook

© 1990 Center for Composite Materials, University of Delaware

Our Mission

The mission of this workbook is to quickly and simply introduce the basic concepts behind the Total Quality Design (TQD) philosophy and tools, and to encourage and facilitate the adoption of TQD by the reader into his or her own life.

What's in it for You?

After completing this workbook, you should be able to organize and carry out a TQD project in your place of business. TQD projects may involve new business products, improvements of existing products, new or improved processes, or new or improved organizational structures. With the TQD process, you should experience a reduction of time to market (time from concept to reality) and an improved final "product", whatever that product might be.

What's in it for Us?

We have three main purposes in preparing this workbook:

- To improve the designing, decision-making, and product developing skills of our audience.

- To provide an aid in the successful planning and execution of the product development process

- To gather data to further improve our product: the TQD process

With the third purpose in mind, we solicit any and all comments regarding this workbook or any other aspect of TQD. You may reach us at the following addresses:

Vistasp M. Karbhari
Dick J. Wilkins
Center for Composite Materials
University of Delaware
Newark, DE 19716
(302)-451-8149

John M. Henshaw

Mechanical Engineering Dept.
University of Tulsa
Tulsa, OK 74104-3189
(918)-631-3002

How to Use this Workbook

The following are some suggestions...

Scan the sections in the Table of Contents

Each section begins with a mission statement that summarizes the contents of the section. Read the mission statements and the fundamental definitions that follow.

Study the checklists at the beginning of each section.

Like the TQD process itself, this workbook is designed to be as sequence-free as possible. Feel free to browse the sections that interest you the most.

Read the whole thing once, and then tackle the exercises at the end of each section.

Many of the exercises build on each other from one section to the next. Thus, you may find it helpful to complete the exercises in order beginning with the first section. Do not, however, feel that you must finish every detail of the exercises in one section before you move on to the next set of exercises. Many times, your answers in one section will stimulate those in previous sections.

Table of Contents

What is TQD?

Total Quality Design (TQD) is the design component of Total Quality Management (TQM).

TQD has evolved in response to competitive imbalances that currently exist in the world economy. TQD seeks to correct these imbalances by giving engineers and others involved in product development a set of tools and guidelines for developing better products faster. TQD does this by concentrating on the conceptual phase of development, where the most critical decisions are made. TQD is also a means for encouraging creativity and innovation during the product development process.

TQD is made up of NINE recognizable components.

These nine components represent stages that any development process must pass through. Each component has a dual nature: a "creative" side and a "disciplined" side. The order and duration of the phases will depend on the situation, but there exists a fundamental set of tools and guidelines. Each component will be described in detail in this workbook.

TQD itself can be represented graphically in several ways.

On the next page, TQD is shown in "mindmap" format. A mindmap is a form of outline that removes the need to list things in chronological order. This format allows the nine fundamental components of TQD, along with some of the characteristics of each, to be shown in a "concurrent" manner that does not imply the order or duration of the components. On page 5, TQD is represented as a GANTT chart, a more traditional format that does imply such things as order and relative duration.

TQD - Mindmap Format

CREATE
EVALUATE

Mission

Goal
Schedule
Scope

Customers

Primary
Secondary
Partners
Share-holders

Customer Wants

Satisfaction
Qualitative
Categories
All-Inclusive

CREATE
EVALUATE

Team

Facilitator
Customer
Manufacturer

What is TQD?

Products
Processes
Organizations

Benchmarking

Improve it or use it
Products
Processes
Organizations

Go/No-Go Review

Decide!

Quality Metrics

Quantify
Compare
Prioritize

Concept Selection

Compare
Eliminate
Expand
Synthesize

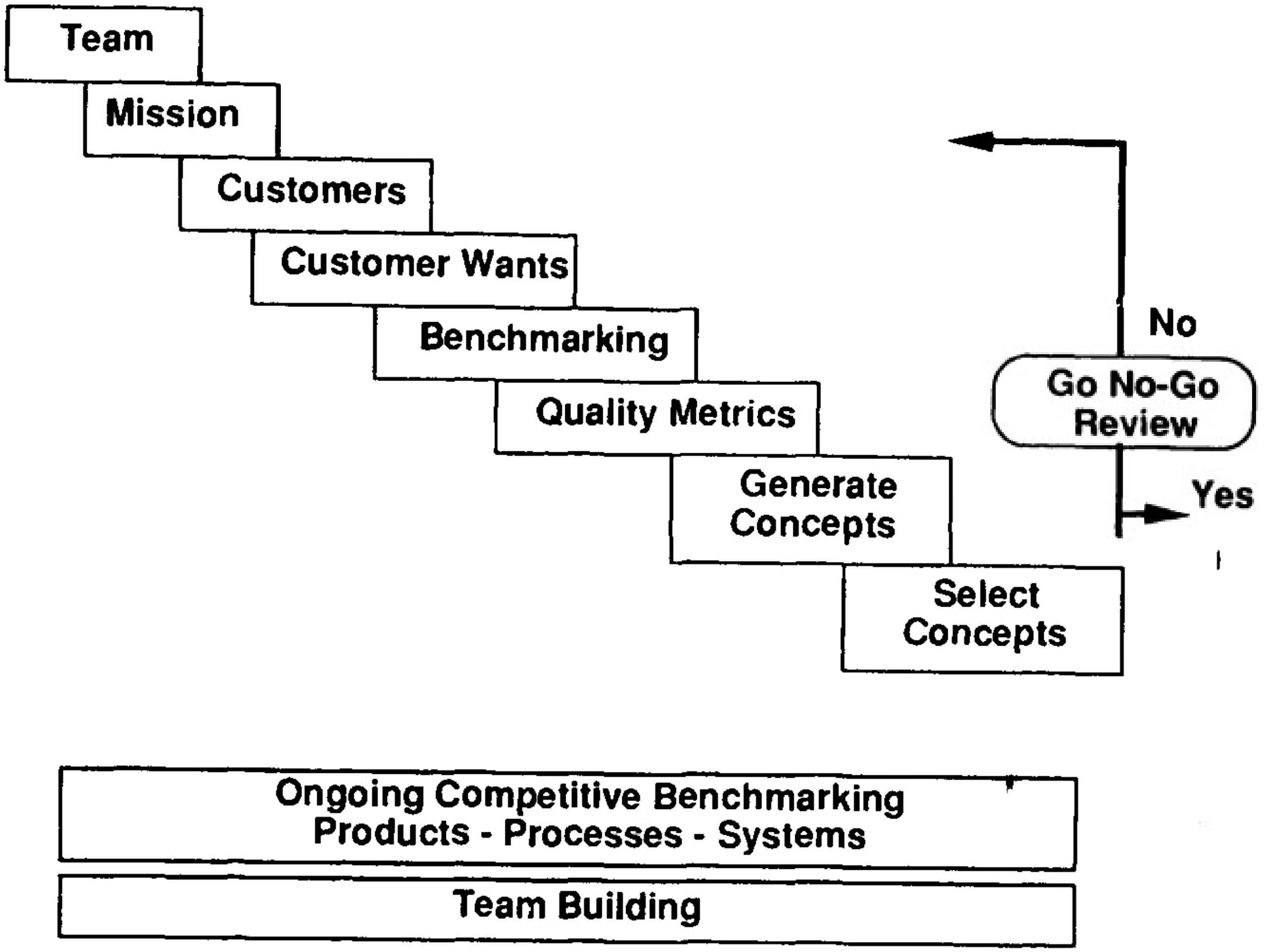
Concept Generation

Materials
Configurations
Processes

CREATE
EVALUATE

CREATE
EVALUATE

TQD - GANTT Chart Format



Team

Mission

Customers

Customer Wants

Benchmarking

Quality Metrics

Generate Concepts

Select Concepts

Go No-Go Review

No

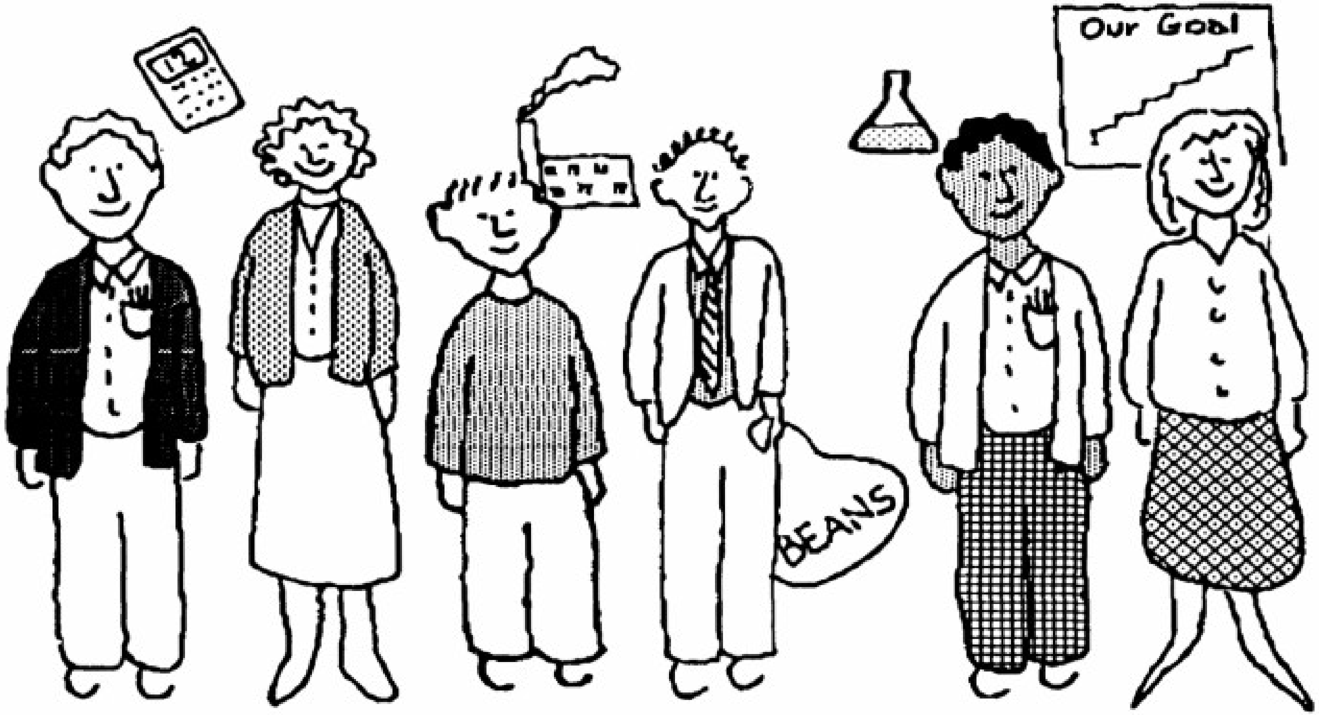
Yes

Ongoing Competitive Benchmarking
Products - Processes - Systems

Team Building

The Team

The unit cell of TQD is the team. The nucleus of the unit cell consists of a facilitator, a primary customer, and a producer. Other team members can be added as resources permit. The best team member is one that is willing and able to make good decisions within his or her own area of expertise, and is willing to collect and evaluate information from other team members and outside experts (consultants) for decisions outside the area of expertise.



Team Checklist

Upon completion of this section, I should be able to:

	Understand the difference between group and team behavior
	Know what roles constitute the nucleus of the TQD team
	Understand the difference between team members and consultants
	Describe some team opportunities in my own work.

Team Facilitator

The TQD Team Facilitator leads not in the sense of having a great deal of arbitrary decision-making power, but more in terms of team organization, team building, and facilitation of the product development process.

Team building is simply the process of ensuring that the team acts like a team throughout its existence. Team building involves elements of management and behavioral psychology.

Primary Customer

It is very important that the voice of the primary customer be represented on the TQD team. The best way to do this is by including the primary customer on the team. If this is not possible (the reasons for this may vary), then someone who very closely represents the primary customer must be included. This may be someone with strong marketing influence and background, a field engineer or representative experienced in dealing with the customer, or someone else who understands through experience the main wants of the primary customer.

Producer

The producer is someone with responsibility for and understanding of the steps necessary to turn design information into reality. For many engineering efforts, this person is the manufacturer. In architecture, it is the builder. The producer must be represented on the TQD team because it is the best way to ensure that the transformation from design to reality takes place as well and as quickly as possible. It is necessary that the entire process be treated as one that converts materials (or services) into goods of economic satisfaction, i.e., production decisions should be business decisions as well.

Groups versus Teams

Since the Dawn of Man, humans have found that working in groups is an indispensable part of a great many important activities. The performance of groups of people working together, however, varies greatly. What we call a "team", as defined below, tends to produce much better results than a mere "group".

Some of the main differences between group behavior and team behavior are as follows:

- Groups tend to assume they are together mainly for administrative purposes, while teams recognize their independence from the rest of the organization and realize that both personal and team goals are best accomplished through mutual trust and support.
- Group members are typically told what to do rather than deciding, as teams do, in a concurrent fashion, what is the best course of action.
- A climate of distrust, or "me versus them", is much more likely to exist in a group than in a team.
- Communication is much more open and effective in a team than in a group. In a group the "right hand often doesn't know what the left is doing".

Team Members versus Consultants

A team member has decision-making responsibility. Consultants are called upon to render their opinion in specific areas of domain knowledge. The opinions of consultants are just that: opinions. The ultimate decision-making power lies with the team.

What kind of individual makes a good TQD team member?

Some of the most important characteristics of good team members follow:

- Good team members are willing and able to work and make decisions in areas outside their specialized areas of expertise.
- Good team members are specialist in specific areas and generalists in a wide variety of others.
- Team members understand that both individual and team goals and rewards exist, and that they are not mutually exclusive.
- Team members excel at verbal, written, and graphic communication.
- Team members prefer situations where they can help define their goals and missions.

The Groups/Teams in Your Life...

How many separate, identifiable work groups do you belong to?

How many members does each work group contain?

Which of the groups have leaders, and what is the leader's function?

In how many of your groups is there strong customer representation?

In how many of your groups is there strong production representation?

In how many of your groups is there a strong financial representation?

Would you characterize the work groups you belong to as "groups" or as "teams"?

What characteristics of group-like and team-like behavior do you observe in your own work?

How would you go about starting a new team in your work area? What administrative and cultural obstacles would you have to overcome?

Team Exercises

Write down several opportunities for team efforts in your workplace. Consider possibilities such as new product development teams, purchasing teams, publishing teams, facilities teams, strategic planning teams, and so on. Try to think of some non-traditional areas where teams might be able to help.

Consider the makeup of each of the teams. Who would be the leader? The voice of the customer? The producer? Who else might you like to include on the teams? Think about the positive attributes of your co-workers that would make them good team members.

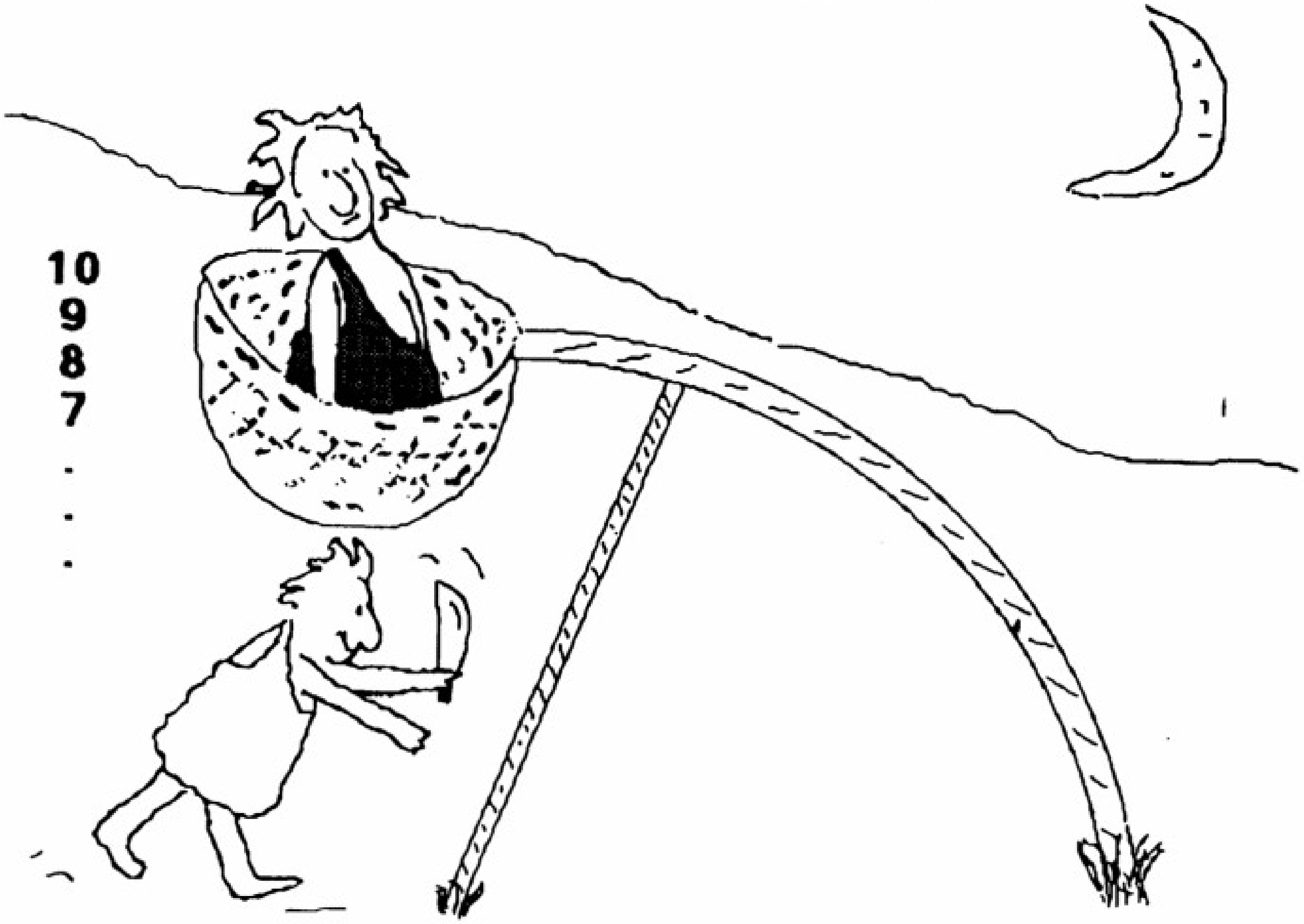
Imagine yourself as the leader of one of these teams. What would you try to accomplish at the first meeting?

How would you go about determining the mission of your team?

Implement one or more of your teams!

The Mission

The most important elements of the TQD mission are the goal and the schedule. The goal must not anticipate the method of solution, and the schedule must interact concurrently with the goal and the customers, through the team.



Mission Checklist

Upon completion of this section, I should be able to:

	Describe the main elements of a TQD mission
	Write a good mission statement
	Understand the concept of *concurrency* as it relates to the mission
	Describe the missions for some of the teams I created in the Team section

Elements of the Mission Statement

Goal

The goal is the most important part of the mission statement. The goal must capture, in global terms, the most important objective of the TQD project, without predetermining in any way the technical means by which the goal will be accomplished.

Schedule

The schedule is an often overlooked part of the mission statement. The schedule element of the mission statement will usually not be as detailed as the schedules developed in later TQD activities, but it is nonetheless important to include scheduling aspects in the TQD mission statement.

Scope

The strategic decisions made in terms of the goal, schedule and cost define the scope of the project. An efficient project team is essential in determining the scope of the mission in terms of economic and productivity based tradeoffs between schedule and cost associated with the mission. Scope forces production decisions to be made as business decisions. This enables efficient planning for project execution.

Resource Allocation

Resource allocation, in terms of the mission statement, refers to two main elements: money and staffing. Great care must be taken when setting mission objectives with respect to resources. For this reason, the concurrency element of the mission statement becomes very important.

Concurrency

Concurrency, in the context of the TQD mission, means that the mission statement is forged by the team and its management in a concurrent fashion, not handed down from on high "etched in stone". Tradeoffs among the goal, schedule, and resource allocation are taken into account in developing the mission statement. Tradeoffs among the mission, the team, the customers, and their wants may also be necessary, as discussed in later sections.

Your Teams' Missions...

How well defined are the missions of the teams you work on?

Are their mission statements written down for each team member's benefit?

What elements of the mission statements are present? Absent?

Do the teams have any influence over what their missions are?

Are their mission statements "cast in stone" or flexible in terms of fulfilling changing needs and wants of the customer?

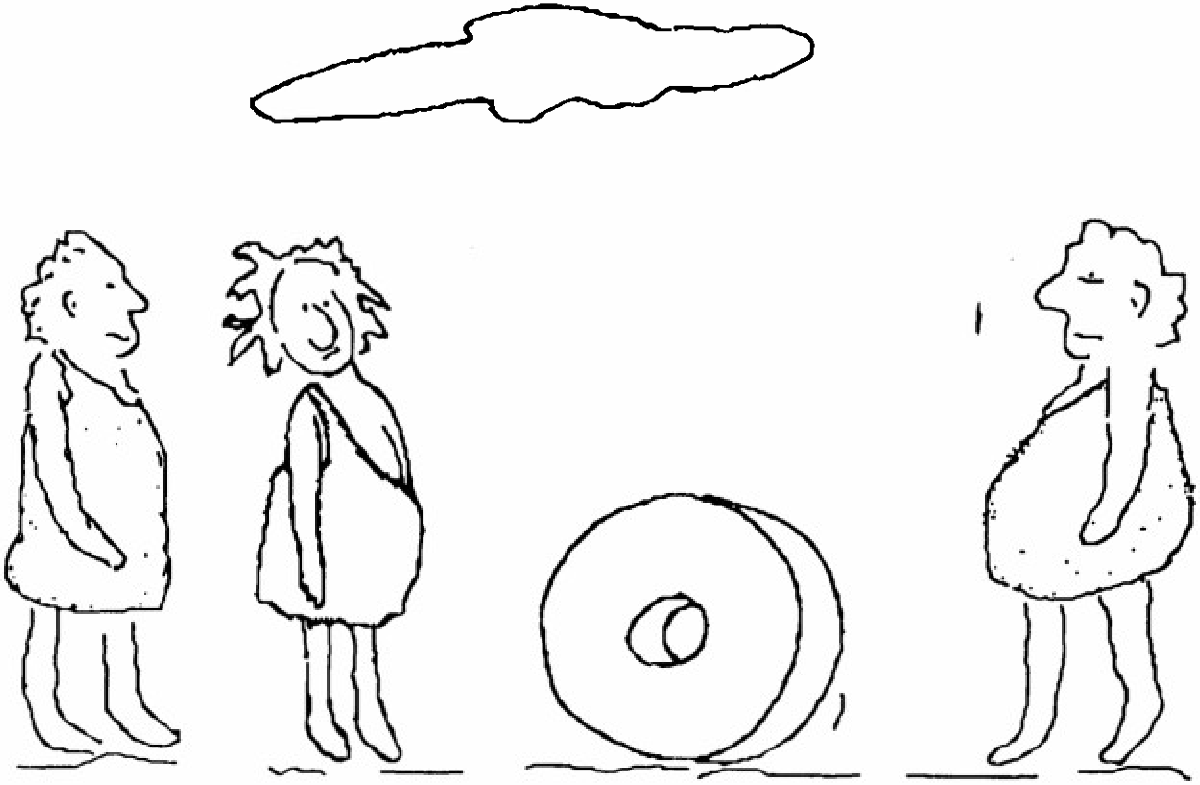
Mission Exercises

Refer to the team exercises in the last section. Derive mission statements for each of the teams you created. How might you make the goals more (or less) ambitious? If you did so, how would that influence the schedule?

Derive a set of mission statements for the same project, varying the schedule element of the project. That is, develop a mission statement to accomplish a goal in one week, one month, six months, and one year. How does the goal vary with the length of the schedule?

Customers

A customer is someone whose wants and needs must be satisfied through the efforts of the TQD team. Customers should be identified by name. All categories of customers must be discovered, particularly those whose wants conflict with other categories. Allocate resources to satisfy customers; do not mistake partners for customers.



Customer Checklist

Upon completion of this section, I should be able to:

☐	Understand the concept of customer categories
☐	Know the difference between primary and secondary customers
☐	Know the difference between a customer and a partner
☐	List the customers for the missions created in the exercises of the previous section

Customer Categories

Every TQD project is likely to have customers that fall into distinct categories. This refers not only to the variety of, for example, the consumers who will purchase a common household product, but to groups of customers that have fundamentally different relations to the product. Two classic examples of this follow: In products developed for the U.S. Department of Defense, there are several distinct customer categories. There is of course the soldier, sailor, or pilot who will be the most intimately involved with the product, but there is also a series of civilian and military customers falling into different categories with responsibility for the acquisition of the product . This series of customers leads ultimately to the Pentagon and the Congress. The second example is that of a consumer product that must satisfy not only the consumers who purchase it but also the customers at any public or private agencies that regulate or evaluate it.

The wants and needs of the various categories of customers are likely to vary. It is not unusual for them to be at odds with one another.

Customer Names

It is critically important to identify specific customers by name. Only in this way can the team hope to uncover the true wants and needs of the customer. The temptation to avoid this step is great, but so are the dangers. Know your customers by name. If you have a customer category to which you cannot match a name, find one.

Primary Customers

The degree to which the customer categories vary with respect to their wants is important. If this variety is too great, the TQD team may need to redefine its mission. The primary customer is usually taken to be the person or persons in most intimate contact with the product. For a product, that is most often the user. For a process, it is those with responsibility for the output of the process. For an organization, it is those that the organization serves.

Secondary Customers

Secondary customers are referred to in the above section on customer categories. These customers have very real and important wants and needs, but they do not fulfill the above definition of primary customer . These could include a stock holders in the company, for whom the wants are economic in terms of cash flow and return-on-investment, rather than specific product needs.

Customers and Partners

If quality is to be built into a product, two main categories of customers (and their needs) must be kept in mind at each stage of the product development process:

- the primary customer
- the individuals or teams associated with the subsequent stages in the production process

Thus at each stage there is a downstream customer and everyone involved has an internal customer who receives goods of satisfaction. These are not merely customers, but partners in the production process.

Your Teams' Customers...

Does each of your teams have a well-defined set of customers?

What about the teams that aren't "selling" something in the traditional sense?

Do your teams ever treat internal partners as if they were customers?

How many categories of customers can your team identify?

Are all the customers voices considered throughout the product development process?

Customer Exercises

Refer to the mission exercises in the last section. List the customers for each of the missions you wrote statements for.

For each mission:

How many distinct categories do the customers fall into?

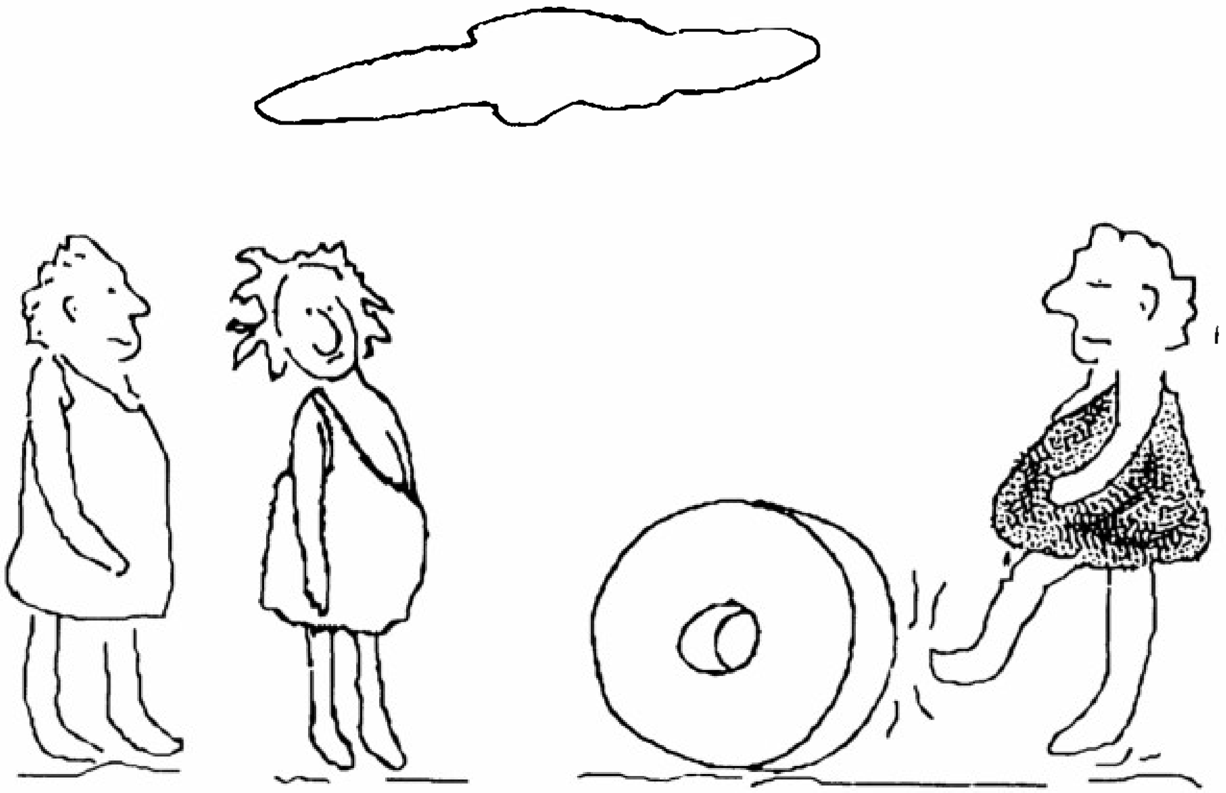
Can you think of specific individuals for each category?

Does your list of customers make you want to reevaluate your mission statement? The personnel on your team?

In general, do you expect to find good agreement among the wants and needs of your various customers?

Customer Wants

Your team's customers are likely to have varying wants. These wants must be discovered for each customer category. This is likely to involve market research and competitive benchmarking (the next section of this workbook) of the competition and of other products. The customer wants, which are not necessarily quantifiable, must be rated on a relative scale as to their importance.



Customer Wants Checklist

Upon completion of this section, I should be able to:

	Understand the creative and disciplinary aspects of determining customer wants
	Carry out a brainstorming session to discover customer wants
	Know how to uncover "tradeoffs" among customer wants
	List the customer wants for the missions created in the exercises of the previous section

Brainstorming for Customer Wants

One good way to discover the scope of wants and needs of your customers is through benchmarking. There are many techniques for brainstorming in general. For the special case of brainstorming for customer wants, several approaches are helpful. Consider each of your named customers in turn. Focus on what functions they might want - and make lists of verbs. Next focus on what features they might want - and make lists of nouns. Finally, focus on what qualities they might want - and make lists of adjectives.

Brainstorming is NOT a substitute...

for good market research! Brainstorming can supplement and even help to guide market research, however.

Relative importance of customer wants

At this stage the relative importance of the customer wants should be evaluated. A suitable scale should be chosen to prioritize the list of customer wants (for example, a scale of 1 to 5, with 5 being the most important).

Conflicting customer wants

The lists of customer wants that you generate through brainstorming and market research are likely to contain conflicts. One customer wants your product to be inexpensive, while another wants it to be high-performance. A conflict like this one may be partially or completely resolved through an innovative concept, but what of a more fundamental conflict, where two customers want things that are diametrically opposed to one another? This may involve reconsideration of the team's mission.

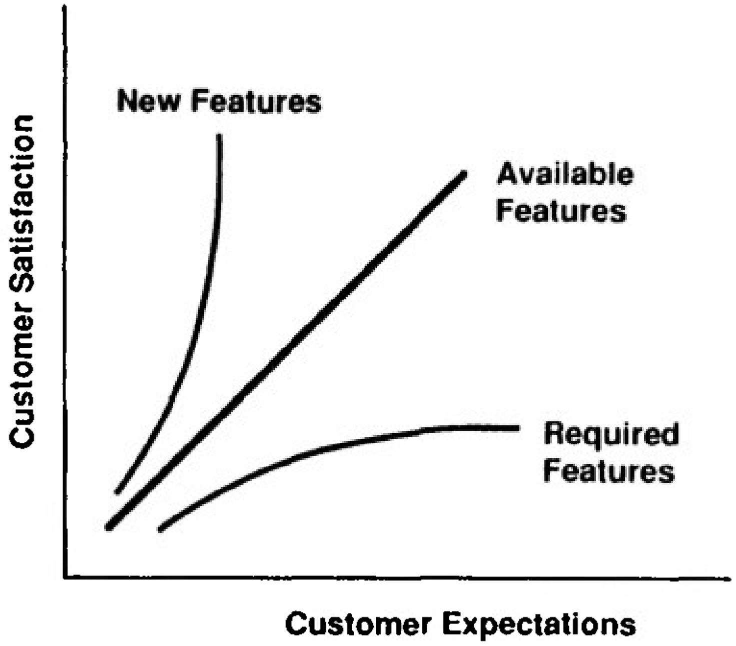
Revealing Customer Wants Conflicts

A table may be constructed that uncovers the conflicts among customer wants. Such a table, shown below, consists of an n x n matrix where n is the number of customer wants. Include the relative importance of each want in the table.

	Want #1 rating#	Want #2 rating#	Want #3 rating#	Want #4 rating#	Want #5 rating#	Want #6 rating#
Want #1 rating#	●					
	Want#2 rating#	●				
		Want#3 rating#	●			
			Want #4 rating#	●		
				Want #5 rating#	●	
					Want #6 rating#	●

Wants, Expectations, and Satisfaction

Product (or service) quality must not only meet customer expectations, it should exceed them. This ensures customer satisfaction, and loyalty.



At the lowest level, one provides products of acceptable quality. An improvement in product quality at this level is rarely perceived by the customer, although a decline in quality is (i.e. increase in the life of a fan belt etc.)
The second level pertains to the addition of optional features (cruise control, anti-lock brakes etc.).
At the highest level of quality perception, new features must be added to existing products. This involves innovation, creativity, and an ability to gauge the customers inner wants. The TQD process helps in attaining this level of customer satisfaction.

Evaluating Customer Wants Conflicts

Each element of the matrix contains an evaluation of the magnitude of the correlation between the two wants in question. Various symbols can be used to indicate the following kinds of correlations: strong negative, weak negative, neutral, weak positive, and strong positive.

The utility of this table lies in revealing (and thus allowing evaluation) very early in the development process, where the wants of customers may come into conflict. Similar tables will be used elsewhere in TQD to reveal other "trade-off" phenomena.

TQD Software

A set of TQD software tools, developed at the Center for Composite Materials, facilitates this process, by setting up each of the tables described in this and subsequent sections and by performing the calculations that many of the tables require. This allows the TQD team to perform "what-if" trade-off studies simply and efficiently at the very early stages of their projects. The TQD software is referred to and more fully described in most of the remaining sections of this workbook. TQD software is available through CCM.

Current and Desired Performance

The current and desired performance of your product in terms of each of the customer wants should also be tabulated:

	Importance Rating	Current Performance	Desired Performance
Want#1			
Want #2			
Want #3			
Want #4			
Want #5			

Once again, these ratings are qualitative, on an arbitrary (one-to-five) scale. These particular ratings are important because they are used in the calculations of the most important Quality Metrics in a later section.

Customer Wants Exercises

Refer to the customer exercises in the last section. Brainstorm the customer wants for each of the missions you listed customers for.

For each list:

What, if anything, is likely to be missing from your customer wants? What market research does the team need to do?

Determine the relative importance of each of the customer wants.

Construct a table to discover any conflicts among customer wants.

Are there any strong negative correlations among the customer wants? If so, what are the relative importances of the wants in question?

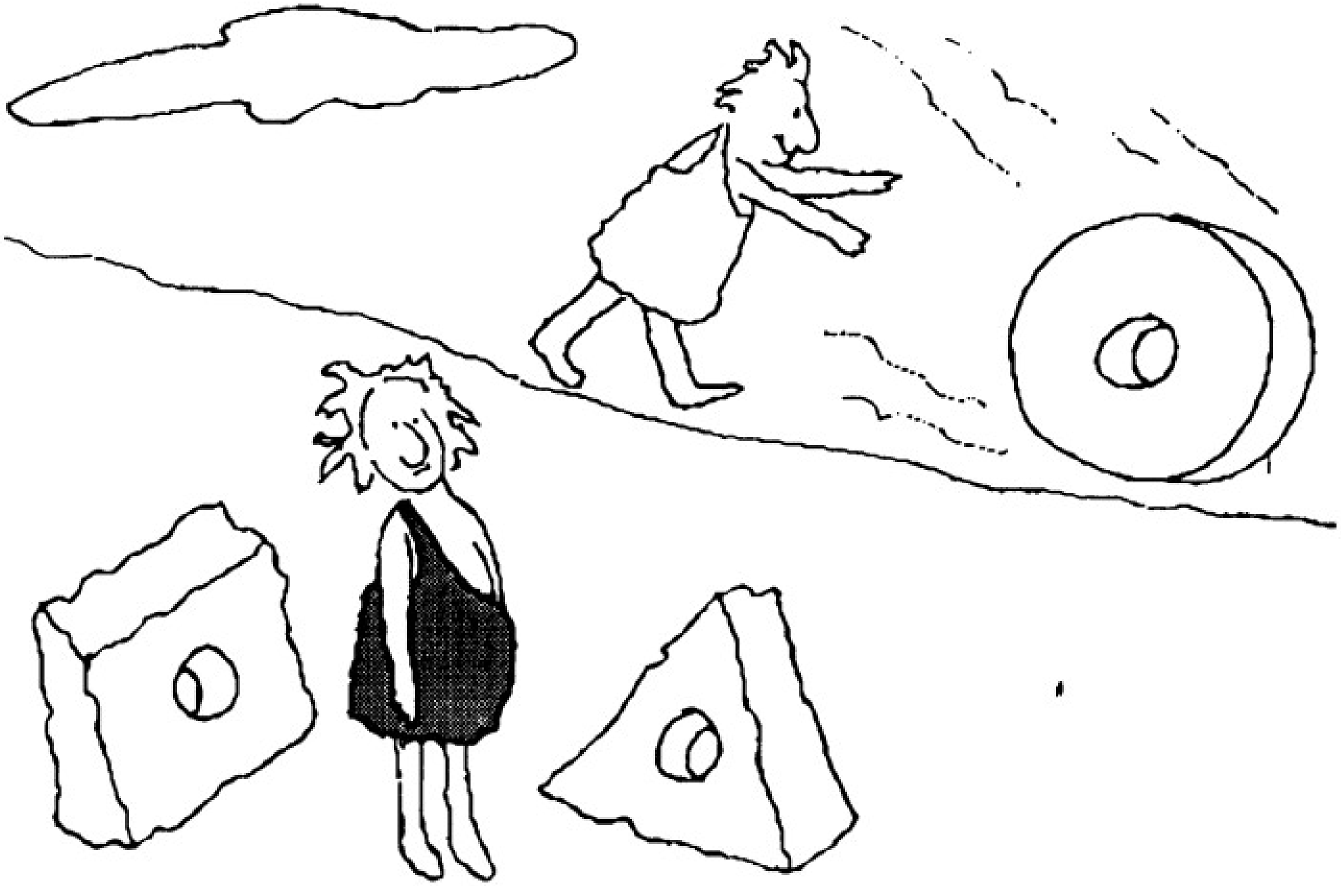
Discuss the possible resolutions of these conflicts in terms of the customers and the mission.

Which levels of product quality (and customer satisfaction) are you likely to achieve through your products?

Create tables listing the relative importance, current performance, and desired performance for your projects.

Competitive Benchmarking

The First Law of Benchmarking says "If you can't improve on it, you must use it". Those products and processes that are competing for your customers must be discovered. Their ability to provide the customer wants and Quality Metrics (see the appropriate sections) must be rated on a relative scale.



Benchmarking Checklist

Upon completion of this section, I should be able to:

	Understand both the specific and general roles of benchmarking in the TQD Process
	Understand the magnitude of resources required to benchmark properly
	Describe the relationship between benchmarking to creativity
	Outline a benchmarking plan for the continuing projects in the exercise sections

Benchmarking as a Way of Life

Benchmarking has both specific and general places in the TQD Process. In the GANTT chart representation of TQD on page 4, you will notice that benchmarking appears twice, once between Customer Wants and Quality Metrics, and again at the bottom of the chart. This latter appearance is identified as "Ongoing Competitive Benchmarking - Products, Processes, and Organizations" to indicate that the benchmarking process is not confined to the specific roles that will be described in this section. Instead, benchmarking is something that should always be kept in mind, as you search for and recover "treasures" that can be applied at any stage of the TQD Process.

Everything has benchmarks

Do not assume that the need to benchmark is lessened in the case of "innovative" or "first generation" products. In fact, the reverse may be true. As George Kneller said in *The Art and Science of Creativity*, "...in order to think originally, we must familiarize ourselves with the ideas of others". TQD takes that several steps further. You must familiarize yourself not only with the ideas of others, but also with their products, processes, and organizations.

Benchmarking Products, Processes, and Organizations

Most people involved with product development are familiar with the concept of product benchmarking. This usually takes two fundamental forms: market comparison and "reverse engineering", as discussed below.

Benchmarking processes is more difficult, but at least as necessary. Benchmarking processes often answers the question, "How does material move through the process?"

Benchmarking organizations (or systems) can be more difficult still. It may help to think of the question, "How does information move through the organization?"

Benchmarking and Creativity

As the above quote from George Kneller indicates, benchmarking and creativity are intimately related to each other. For example the ability to "piggyback" on the ideas of others is an important part of the brainstorming process. When you piggyback, you are essentially building on the benchmark of your teammate. The same is true when it comes to benchmarking the products, processes, and organizations of your competitors.

Reactionary versus Proactive Benchmarking

Most everyone is familiar with the reactive form of benchmarking. This process, sometimes referred to as "reverse engineering", involves discovering the important parameters of your benchmarks through disassembly, testing, and similar techniques.

Proactive benchmarking, on the other hand, involves discovering, using, and improving on the ideas and methods of less obvious benchmark sources. For example, while it is obvious if you build cars that you should benchmark the products of other carmakers, it is less obvious perhaps to benchmark aerospace products - for their materials and processes, among other things. This quickly returns us to the concept of benchmarking as a way of life...

Benchmarking Tables

It is useful to construct tables that organize your team's benchmarking data, as shown below:

	Benchmark #1	Benchmark #2	Benchmark #3	Benchmark #4	Benchmark #5
Want#1 rating#					
Want #2 rating#					
Want #3 rating#					
Want #4 rating#					
Want #5 rating#					

Each element of this table will contain a relative numerical ranking (once again, a one-to-five scale has been used in the past) of each benchmark's ability to supply the Customer Want in question. A similar table should be created comparing the benchmarks to the Quality Metrics described in the next section.

Benchmarking Exercises

Refer to the customer wants exercises in the last section. In each case, who is the competition? What are the obvious benchmarks? The not-so-obvious benchmarks?

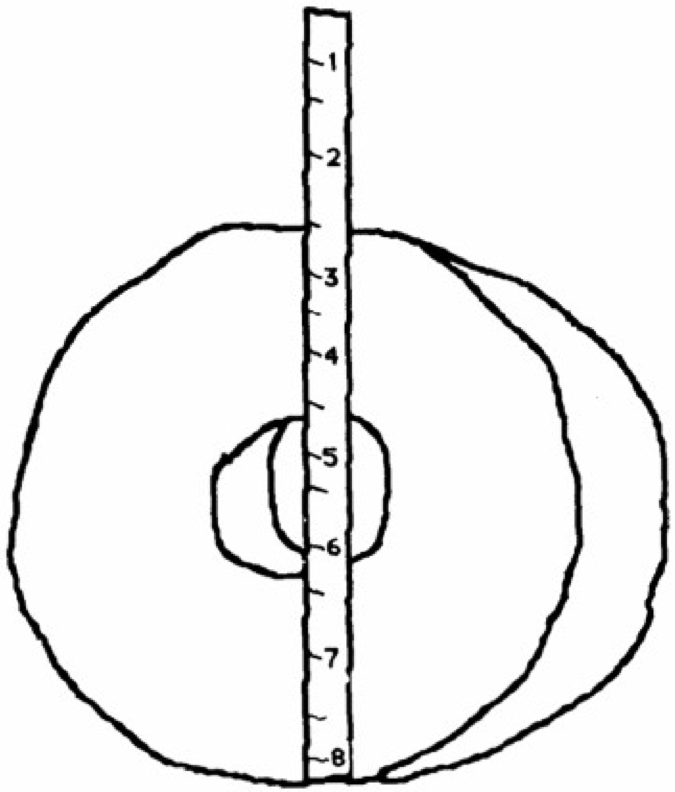
What do you think it would take (resources) to properly benchmark each of these?

For each of your missions, does it make sense to benchmark products, processes, and organizations? Why or why not?

Create benchmark versus customer wants tables for each of your projects.

Quality Metrics

Quality Metrics are the measurable quantities corresponding to customer wants. Quality Metrics must be correlated to Customer Wants, in order to discover which metrics are the most important.



Quality Metrics Checklist

Upon completion of this section, I should be able to:

☐	Know the difference between Quality Metrics and customer wants
☐	Carry out a brainstorming session for Quality Metrics
☐	Correlate Quality Metrics to customer wants
☐	Determine the Quality Metrics, and their correlations to customer wants, for my exercise projects

The difference between Customer Wants and Quality Metrics

The most obvious difference between Customer Wants and Quality Metrics is that the latter must be quantifiable. As discussed below, Quality Metrics correlate to Customer Wants. Those correlations, however, are rarely one-to-one, and they rarely translate directly. Often, the customer wants something that is difficult to measure directly. Thus, the translation from Customer Wants to Quality Metrics is critical.

An Example...*

Customer Wants and Quality metrics for the F-16 jet fighter

While the F-16 is obviously a very complex system, the example of translating from Customer Wants from Quality Metrics for the systems-level concepts is very instructive, and surprisingly simple.

The "fighter mafia" team responsible for the F-16 concept made no bones about who their customer was: the fighter pilot, who has to go up in combat. First they benchmarked the entire history of air combat (back to the Red Baron) and through painstaking analysis discovered the top four Customer Wants.

The four top Customer Wants are:

Surprise Enemy

Outnumber Enemy

Maneuverability

Lethality

* Adapted from *National Defense*, James Fallows, Vintage Books, 1981, pp.95-106

These four wants translate into the following Quality Metrics:

Low visibility range

Low engine smoke

High differential cruising speed

Low usage of "active" electronics

Sorties per day per $MM

"transient performance"

"persistence": fuel fraction (fuel weight/total weight)

Weapon cost (rounds/$)

Weapon reliability (MTBF)

Minimum lock-on time

Kills/opportunity

Minimum set-up time

Later, we will see how the Customer Wants and Quality Metrics correlate for the F-16 example...

Brainstorming for Quality Metrics

Brainstorming for Quality Metrics is a little like brainstorming for Customer Wants in that it does not take the place of thoroughly benchmarking existing specifications and other places where Quality Metrics might be found. However, brainstorming for Quality Metrics can be extremely useful for several reasons:

- It can yield new metrics, or new combinations of existing metrics, which revolutionize the way your team thinks about its product.

- It can reveal "disconnects" between what the customer wants and your team's ability to measure those wants.

One way to brainstorm for Quality Metrics is to get away, for the moment, from any existing specifications and to think in terms of measuring each Customer Want your team has identified.

Correlating Quality Metrics to Each Other

	Metric #1	Metric #2	Metric #3	Metric #4	Metric #5	Metric #6
Metric #1	●					
	Metric #2	●				
		Metric #3	●			
			Metric #4	●		
				Metric #5	●	
					Metric #6	●

In the same way that Customer Wants were correlated to each other, it can be very useful to correlate Quality Metrics to each other, in order to discover trade-offs among the metrics.

Correlating Quality Metrics to Customer Wants

The next critical stage in the transformation from customer wants to finished product is the correlation of Customer Wants to Quality Metrics. This correlation uses a matrix similar to those introduced in earlier sections. An example is shown below.

Correlation of Customer Wants to Quality Metrics

	Customer Want #1	Customer Want #2	Customer Want #3	Customer Want #4	Customer Want #5	Customer Want #6
Quality Metric #1						
Quality Metric #2						
Quality Metric #3						
Quality Metric #4						
Quality Metric #5						
Quality Metric #6						
Quality Metric #7						
Quality Metric #8						
Quality Metric #9						

Each element of the matrix represents the relative magnitude of that particular correlation. The TQD process uses symbols to represent these relative magnitudes: A "++" represents a very strong positive correlation, a "+" represents a strong positive correlation, an "=" a weak positive correlation, and a "-" a negative correlation.

Correlations for the F-16 Example

Quality Metrics	Surprise	Outnumber	Maneuver-ability	Lethality
Low visibility range	++			
Low engine smoke	++			
High differential cruising speed	++	-		
Low usage of "active" electronics	++			
Sorties per day per $MM		++		
"Transient performance			++	
"Persistence" (fuel fraction)		=	+	+
Weapon cost (rounds/$)		+		+
Weapon reliability (MTBF)				++
Minimum lock-on time				++
Kills/opportunity				++
Minimum set-up time				+

F-16...

Again, the details of the enormously complex F-16 system are not important in this example. The example is included to show how Quality Metrics correlate to Customers Wants.

Ranking the Quality Metrics

An important reason for making the above relative comparisons is to allow the ranking of Quality Metrics. In most cases, the product concepts that are generated (see the next section) will be compared (that is, *selected*) on the basis of Quality Metrics. Since there may be quite a large number of Quality Metrics, it is necessary to determine which metrics are the most important, to facilitate the concept selection process.

The mechanism for ranking the Quality Metrics is contained in the comparisons described in the matrix on the previous page. Each symbol (++, +, =, or -) corresponds to a team-defined integer that serves as a weighting factor. A raw score for each Quality Metric is then calculated as follows:

$$\frac{\text{(Weighting Factor)(Importance Rating)(Desired Performance)}}{\text{(Current Performance)}} = \text{Raw Score}$$

The raw scores for the Quality Metrics are then normalized and ordered from the most to the least important.

Because each of the factors in the above equation that go into the ranking of Quality Metrics are somewhat "arbitrary", it is important to be able to quickly and easily change any of these factors to observe their influence on the rankings. TQD software can help...

TQD Software

The CCM TQD software tools facilitate this process, by performing the necessary calculations to order the Quality Metrics. The software also allows the TQD team to play "what-if" games with the weighting factors (example: should a "++" have a weighting factor of 5 or 9? Try it both ways and see what difference it makes). The software contributes to the "concurrency" of the TQD process by allowing these "what-if" studies.

Quality Metrics Exercises

List any sources that might exist for Quality Metrics for your ongoing projects.

Using those existing sources as a starting point, brainstorm for Quality Metrics with your team. Think about combining metrics to create new ones.

Correlate the Quality Metrics to each other, and to the Customer Wants developed earlier. Order the Quality Metrics. Use the TQD software, available from the Center for Composite Materials, if you desire.

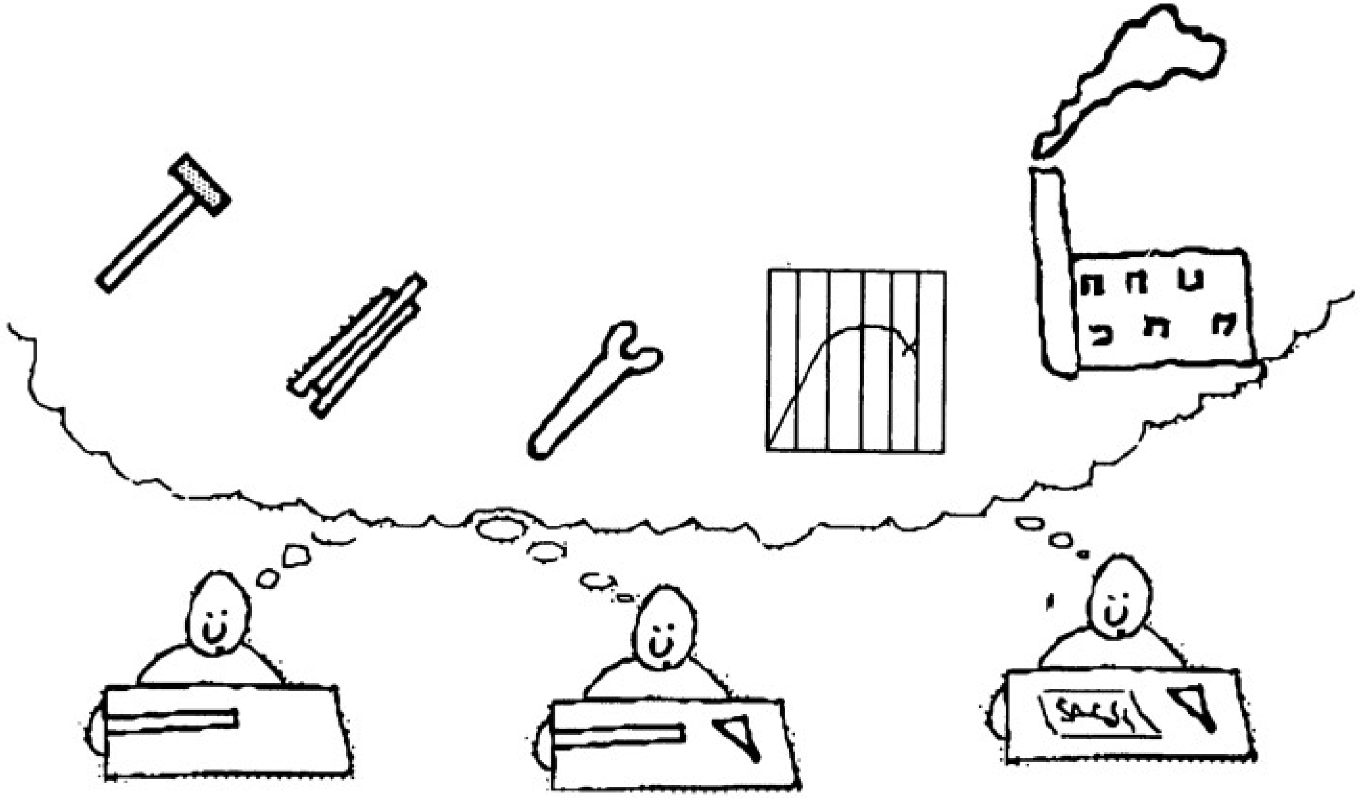
Is there an obvious point in the ordered list below which your Quality Metrics all have a very low ranking?

If so, divide the Quality Metrics into two groups: the higher-ranked of which will be used later in concept selection. The lower-ranked group of Quality Metrics should be retained as a check against the final concept selected by the team.

At this point in your exercises, the "problem" has been rigorosly defined; the solutions come next!

Concept Generation

This is commonly considered the most creative phase of development. In fact, it is just another creative step among many. Quantity is important: many competing concepts are needed. The critical mass of information necessary to call something a "concept" will vary from one project to the next. The team must gain consensus on what a concept is for their project.



Concept Generation Checklist

Upon completion of this section, I should be able to:

	Define a "concept" in the contexts of various kinds of TQD projects
	Understand "design fixation" and how to not only overcome it, but also use it to my advantage
	Use customer wants, benchmarking, and Quality Metrics to generate concepts
	Brainstorm and develop a set of concepts for my exercise projects

What is a "Concept"?

How much, and what kind, of information constitutes a concept can vary with each TQD project. It is the team's responsibility to define a "concept" in the context of their project. One useful rule of thumb may be stated as a definition:

> A concept is a set of information sufficient to make relative comparisons (with other concepts) in terms of the most important Quality Metrics of a given project.

This means, for example, that if your most important Quality Metrics is manufacturing cost per part, your concepts must contain sufficient information to be able to determine the manufacturing cost of one concept relative to another (i.e., not necessarily in absolute terms). This process of relative comparison will be discussed more in the next section.

You might wonder how your team can know how much information is necessary to make these relative comparisons, before such comparisons are even made! This is a difficult problem, and the TQD team is advised to err on the low side of the information balance when it comes to generating concepts. No harm will result: when the relative comparisons are eventually made, it will become obvious that more information is needed.

Design Fixation

The phenomenon of design fixation was alluded to in the Benchmarking section. Design Fixation refers to the tendency to generate concepts whose features bear a strong resemblance to the features of familiar benchmarks. Design fixation can be so powerful that there are those who feel that benchmarking should be avoided because of it! The TQD philosophy, however, is to recognize that design fixation exists and to actively guard against it by benchmarking from widely varying sources, by generating concepts in both individual and team settings, and by generating both a large number and a large variety of concepts.

Concept Generation and Creativity

Concept generation is commonly thought of as THE creative stage of engineering design. As we have seen, however, it is just one creative stage among many. There is both a creative stage and an evaluative stage in nearly every aspect of TQD. At the concept stage, *generation* is creative, and *selection* (see the next section) is evaluative. But the generation and selection of concepts are almost inseparable (concurrent) activities.

Concept Generation and Concurrency

Throughout the TQD process, team members are likely to have ideas that could be admitted as concepts. This fact can be extremely helpful to the TQD process. Team members should be encouraged to discuss these ideas, even in the very early stages of the process. Such discussions can aid in the proper determination of customers, their wants, or other aspects of TQD.

Brainstorming for Concepts

Different methods exist for brainstorming for concepts. One that has worked well in past TQD projects that involve physical products (as opposed to processes or systems) is to brainstorm in turn on each of the three cornerstones of product design: manufacturing processes, materials of construction, and configuration. For many projects, a unique process, material, or configuration may be all that is necessary to create a new concept. Even for those projects where more information is needed, this concept generation technique is useful in generating a large number of widely-varying concepts.

Concepts need not be restricted to only those possible with current technological capabilities. The ability to plan for potential modifications for future generations is an important aspect of good successful product development for products with short life cycles between generations.

It is also helpful to use both Customer Wants and Quality Metrics to aid in the concept generation process. The differences in the items in the two lists can trigger new concepts.

The Language of Concepts

The language of concepts, more than any other stage of TQD, is the sketch. TQD team members must be efficient, prolific and accurate sketchers. This will aid not only in the team's concept generation sessions, but also in concept selection.

Those who are not fluent in the language of concepts would do well to study the works of Betty Edwards:

Drawing on the Right Side of Your Brain and *Drawing on the Artist Within.*

While these general books on drawing and creativity are not written specifically with concept generation (or even design or product development) in mind, they can increase the literacy, and thus the effectiveness of the TQD team member.

Concept Generation Exercises

Brainstorm for concepts for your ongoing projects.

Observe any signs of design fixation. How would you overcome these?

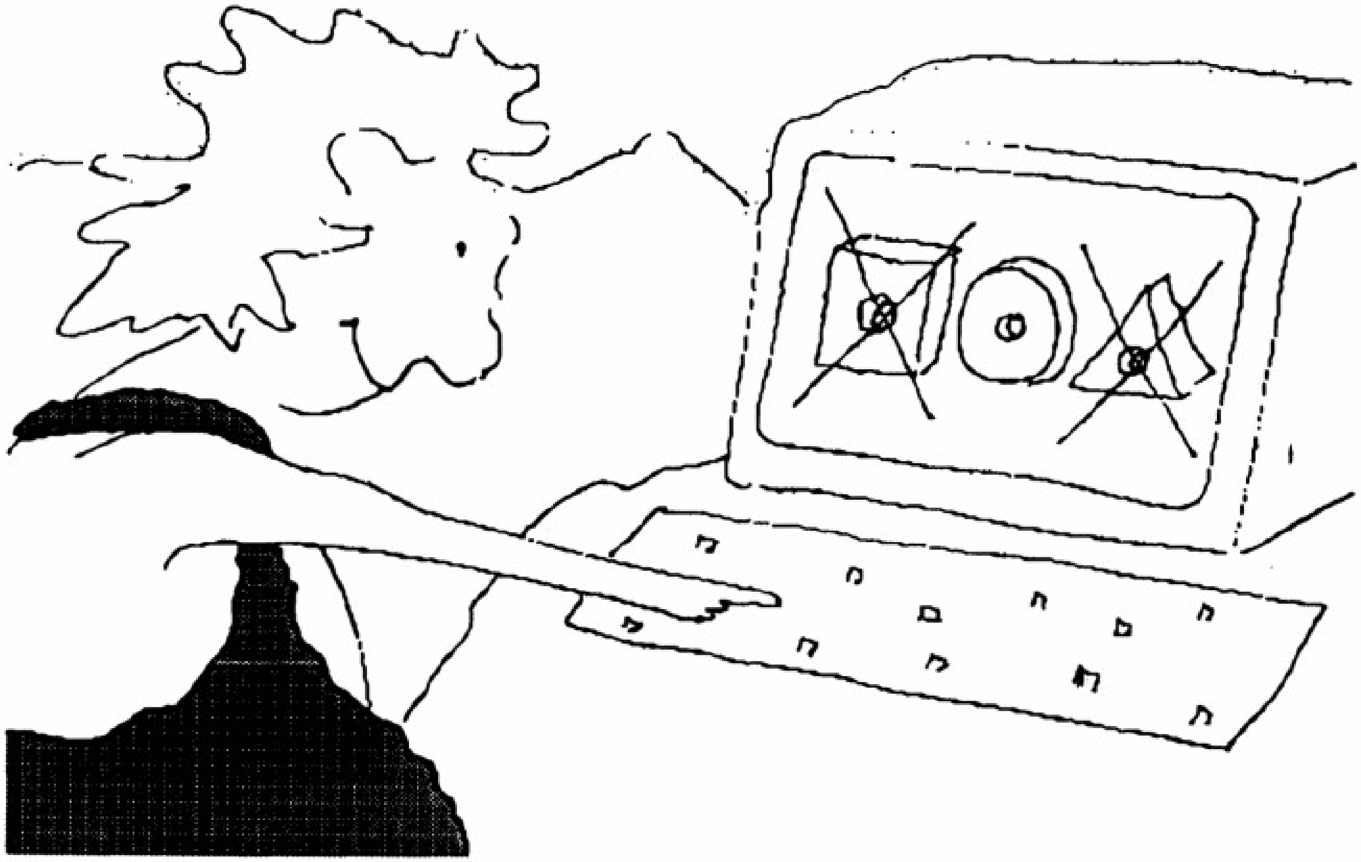
How did you define the amount of information necessary for admission as a "concept"?

Which were more helpful in generating concepts: Customer Wants or Quality Metrics?

Were all the quality metrics defined before concept generation, or were some formulated as a consequence of it? Why?

Concept Selection

The team is unlikely to have the resources to develop each of the concepts generated. The large number generated must be reduced to the best one or two. A process of relative comparison among concepts, with the most important Quality Metrics used as criteria, is employed to eliminate weak concepts.



Concept Selection Checklist

Upon completion of this section, I should be able to:

☐	Understand and apply the Pugh process for concept selection to various kinds of TQD projects
☐	Understand the role of the benchmark in the concept selection process
☐	Discover knowledge gaps for various concepts, and know their role in the selection process
☐	Use the concepts and Quality Metrics for my exercise projects to select the most invulnerable one or two concepts

The Pugh Process

Stuart Pugh's concept selection method is one of the simplest, most practical, and most effective of any of the TQD tools. The Pugh method evolved over a period of years in order to combat the problem of "conceptual vulnerability," that is, weak or vulnerable concepts that don't have a chance of being developed into successful products no matter how much effort and skill goes into the subsequent design work:

> One of the most difficult, sensitive, and critical problems in design, both in teaching and in practice, is the selection of the best concept with which to proceed to detail design and ultimately manufacture... Primarily concerned with the avoidance of conceptual vulnerability brought about by lack of thoroughness in conceptual approach, this, by definition means the emergence and selection of the best and strongest concepts. - *Stuart Pugh*

The Concept Selection Matrix

The foundation of this method is a matrix of generated concepts versus the most important Quality Metrics. The elements of such a matrix are shown below:

	Benchmark Concept	Concept #1	Concept #2	Concept #3	Concept #4
Quality Metric #1	B	+, -, s, or ?	+, -, s, or ?	+, -, s, or ?	+, -, s, or ?
Quality Metric #2	E N	+, -, s, or ?	+, -, s, or ?	+, -, s, or ?	+, -, s, or ?
Quality Metric #3	C H	+, -, s, or ?	+, -, s, or ?	+, -, s, or ?	+, -, s, or ?
Quality Metric #4	M A	+, -, s, or ?	+, -, s, or ?	+, -, s, or ?	+, -, s, or ?
Quality Metric #5	R K	+, -, s, or ?	+, -, s, or ?	+, -, s, or ?	+, -, s, or ?
Number of '+'					
Number of '-'					
Number of 's'					
Number of '?'					

Choosing the Benchmark Column

The benchmark column is the column against which all the generated concepts will be compared. Since the benchmark will be changed from one concept selection iteration to the next, there is no "right" or "wrong" benchmark to choose. A strong competitor, or the current generation of your team's own product, is often a good starting benchmark.

Comparing Concepts: Completing the Matrix

After the concept selection matrix is set up (concepts and critical Quality Metrics generated, and Benchmark column chosen), the process of relative comparisons begins. A given element in the matrix is filled out by comparing its concept (column) to the critical want (row) to that of the corresponding element for the benchmark concept. The element is designated as better than the benchmark, "+", worse, "-", the same, "s", or "?", in which case the element cannot be evaluated.

Dealing with Knowledge Gaps

A "?" in the concept selection matrix is known as a knowledge gap. Dealing with knowledge gaps is a very important part of concept selection. Knowledge gaps often arise because concepts were not initially generated with enough information. If this is the case, the team must add the necessary information, using the critical Quality Metrics as a guide.

Sometimes knowledge gaps arise because they are associated with immature technology. Filling this type of knowledge gap often requires independent research and development. Depending on the magnitude of work required, this type of knowledge gap can lead to elimination of concepts for the current generation of product.

Other knowledge gaps may be associated with mature technology, but still may require lots of time and money for analysis and resolution. The TQD team is cautioned to remember that the comparisons they must make are *relative*. Relative comparisons are almost always easier to make than absolute ones.

The TQD team can save time by not resolving knowledge gaps for clearly weak concepts.

Changing Benchmarks

As mentioned above, changing benchmarks from one concept selection matrix to the next is an important strategy. By changing benchmarks (from one competitor to another or to one of the team's own concepts), the team gains new insights into its concepts.

Eliminating Concepts

Eventually, the team must begin to eliminate concepts from further consideration. In the TQD process, this is done in a team setting. The team must answer the following question: "Can we agree that the concept in question should be eliminated?" As a guideline, the team uses the results of the concept selection matrices (pluses, minuses, etc.). The concept selection matrix keeps all the relevant information "on the table" at the same time. While this does not guarantee that the "right" decisions will be made or that there will be no disagreements, it does keep the critical criteria sharply in focus.

The elimination process should not be restricted to one of direct reduction. Experience shows that the best approach is one that alternates between generative (creative, synthetic) and convergent (selective, analytic) phases. Controlled convergence allows the creation/synthesis of new concepts that are better defined as reasoning proceeds towards the reduction in the overall number of concepts. Simultaneously, this can lead to the addition of new metrics of comparison that can help in better differentiation between concepts at a more intricate level of detail.

Increasing the Information in the Concepts

As the list of concepts gets shorter, the team can be defining more completely those concepts that remain. (This process of adding information to a concept is, of course, the essence of the design process.)

Concept Selection Exercises

Set up a concept selection matrix for each of your ongoing exercise projects. (If you have been using TQD software, this will be done automatically).

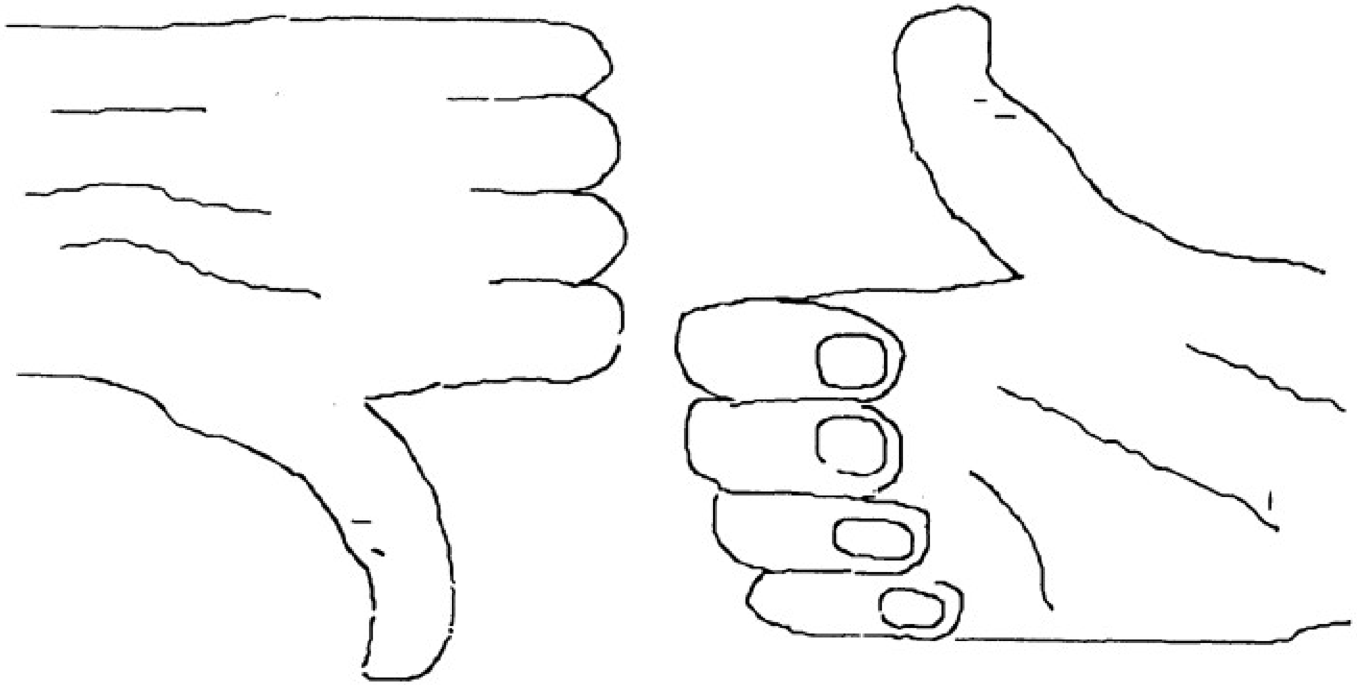
Evaluate each matrix. How many knowledge gaps are revealed? What kind are they?

Resolve as many knowledge gaps as possible. Change benchmarks, and again fill out the matrix.

Using this iterative process, eliminate as many concepts as possible, preferably until only one or two remain.

Go/No-Go Review

Decision time for further development of a project requires that the project be considered guilty until proven innocent. The first such review will usually take place at the conclusion of concept selection.



Go/No-Go Review Checklist

Upon completion of this section, I should be able to:

☐	Decide when and how to hold a go/no-go review for a TQD project
☐	Redefine the meaning of "success" in terms of TQD projects
☐	Understand what happens next for both a go and a no-go result
☐	Hold a meaningful go/no-go review for my exercise projects

When to hold the Review?

Opinions differ on the optimum time to make a "go/no-go" decision regarding the future of a project. Few would argue against the need for such meetings, but just when to hold them can be a problem. The trade-off is this: It is desirable to hold these reviews as early as possible, to avoid wasting resources on a project that is not going to be continued. On the other hand, a review cannot be held too early since there will be no basis on which to make a decision.

Most projects of any size will be reviewed more than once. The TQD process is concerned with the early stages of projects, and thus with the first Go No-Go Review. This review falls very naturally at the conclusion of the concept selection process.

How is the Decision Made?

The Go/No-Go decision is made on the ability of the project to complete the mission. The TQD team typically formulates its own Go/No-Go decision, which it recommends to its management at the formal review meeting. The team's management is ultimately responsible for the final Go/No-Go decision.

Re-defining "Success"

Perhaps the biggest problems with project reviews in general are the cultural and organizational biases against "negative" results. No one wants to be associated with a "failure". The TQD process is not going to eliminate such biases overnight. However, several important principles can help. The first follows directly from the concept selection process. When the selection process, for example, shows that no strong concept exists without critical knowledge gaps, then a "no-go" is in order. The team must recognize that more technology must be generated. The team can remain blameless in this case.

A second situation is more difficult. The team that recommends a positive or "go" decision, but is overruled by its management, is likely to be stigmatized. This is where re-defining success comes in. The TQD principle is to move as quickly and efficiently to the point of the Go/No-Go Review, and then to *decide*. If there are a substantial number of negative decisions, as there should be, the stigma on such results will be minimized.

What Happens Next When it's a "No-Go"

A no-go decision typically returns a TQD project to the point of re-evaluating the customers and the mission. At this stage management and the team have automatically identified the technology gaps, economic issues, and competition conditions that make further development imprudent, thus saving money. Actually, each element of the process is questioned in the case of a no-go.

Time reduction in the TQD process is an aid to the emotional detachment of the team. The shorter the time required to reach the Go/No-Go review, the less likely it is that the team members will be so emotionally attached to their project that they have difficulty reaching an objective go/no-go decision.

Another important function of a no-go decision is to identify critical knowledge gaps for research and development (technology generation), and set time frames and plans for their execution.

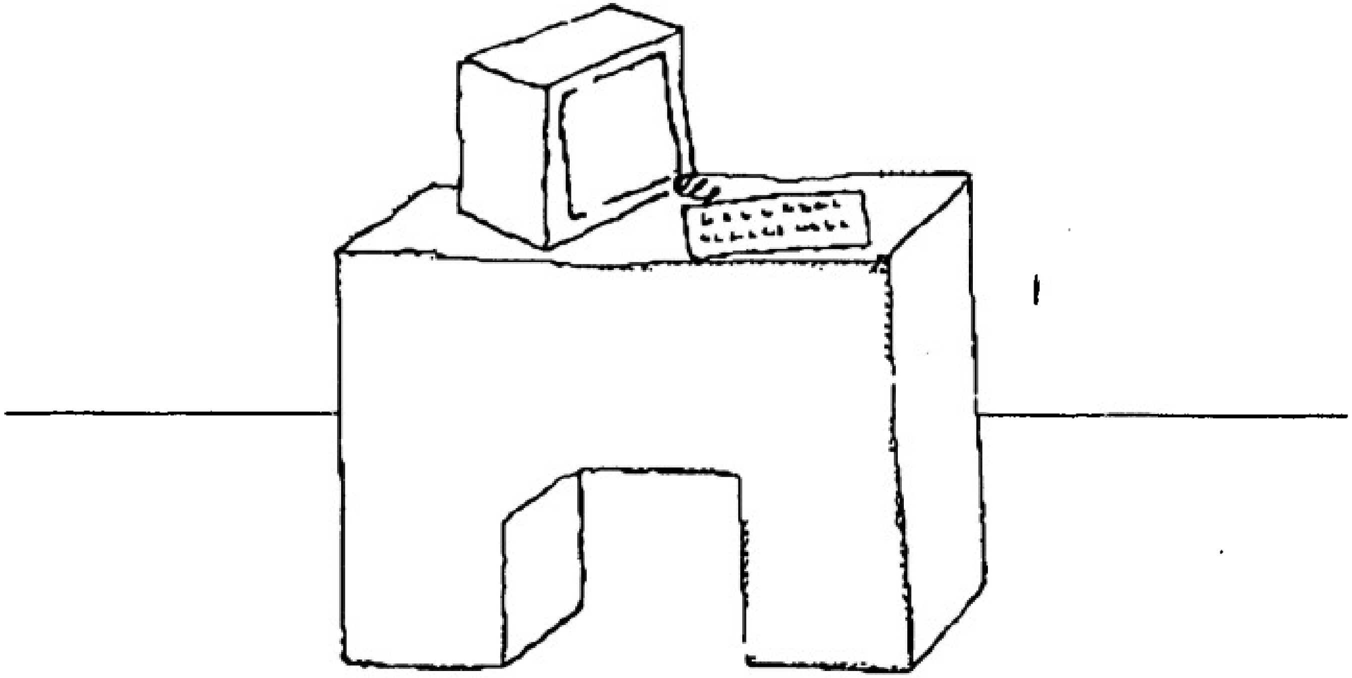
Go/No-Go Review Exercises

Hold Go/No-Go reviews within your TQD team for each of your projects. How many "go's" and " no-go's" are there?

Do you think your teams felt constrained to make the decisions they made?

The TQD Toolkit

Many "tools" are available for use in TQD Projects. A tool is any kind of decision aid, such as a computer program, a book, a chart, or a rule of thumb. One of the goals of our TQD research at the Center for Composite Materials is to provide the TQD team with a complete set of workstation-based tools that, when integrated with the more traditional analysis-based engineering tools, will allow all the life-cycle decisions of a product development project to be carried out within the framework of the same electronic environment.



TQD Spreadsheet Tools

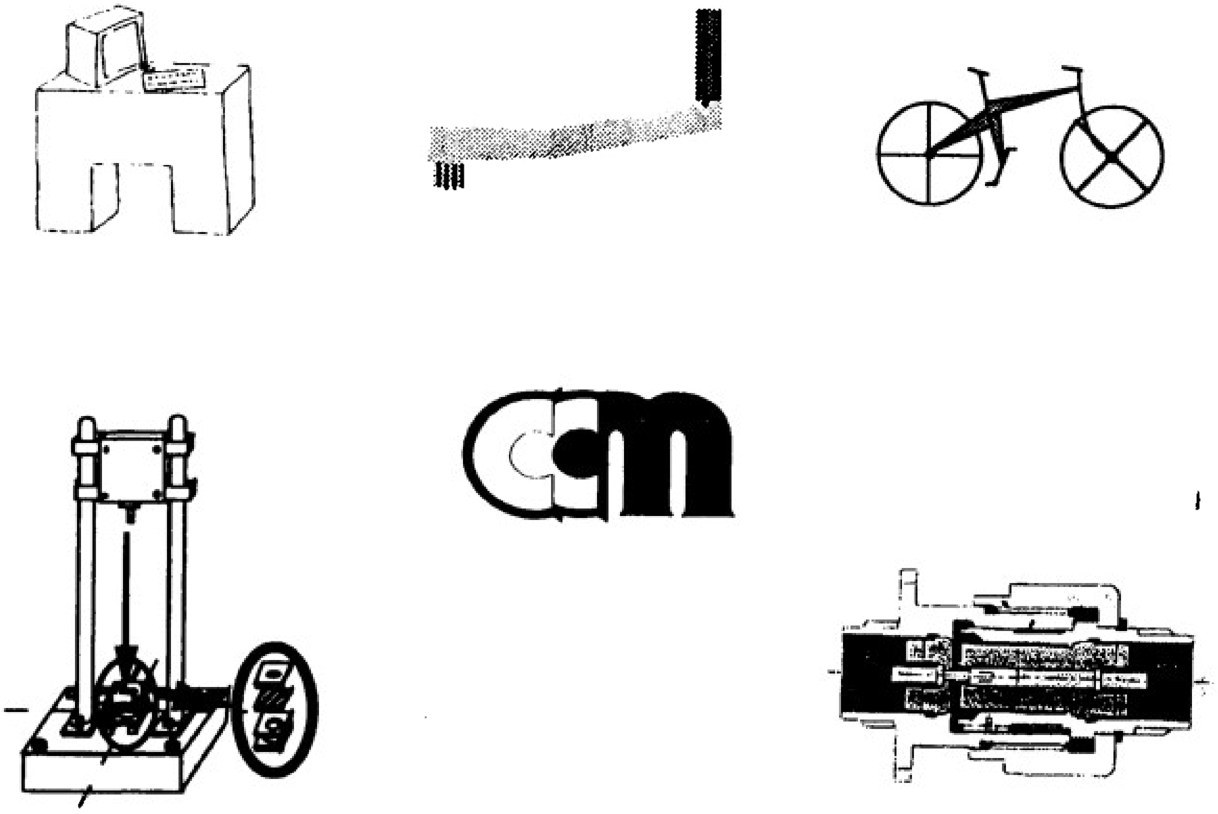
If you have been completing the exercises at the end of each section of this workbook, you may already be familiar with much of the existing TQD toolkit. These tools recreate each of the matrices introduced in various sections of this workbook, using a spreadsheet format. The spreadsheets free the TQD team from a lot of tedious record keeping and calculations, and allow the team to quickly discover the implications of various trade-offs.

Continuous Improvement!

The design research team at CCM is continuously improving and expanding the TQD electronic toolkit. Our mission, restated from above, is to provide the TQD team with a complete set of workstation-based tools that will allow all the life-cycle decisions of a TQD project to be carried out within the framework of the same electronic environment.

TQD Applications

TQD has been applied to a number of projects by teams at the Center for Composite Materials. These projects have involved organizations, processes, and products.



TQD Applications

The illustrations on the previous page show a few of the projects to which the TQD process has been applied. TQD has been applied to organizations (such as the Center for Composite Materials and the American Society for Composites), processes (such as the design process for composites and design-for-impact methods), and products (such as bicycles, electrical connectors, Army gas mask components, and sailboat winch handles).

How Do We Know TQD "Works"?

This is one of the most difficult questions to answer quantitatively. Concurrent engineering approaches of every shape and size are dreamed up and declared a success almost before they are ever applied. Phrases such as "a ten-fold increase in quality", or "a 50% reduction in the time to market" are commonplace in the literature. However, since every project is different, and since each is influenced by so many variables, it is nearly impossible to ascribe such claims solely to improved methods or tools. Parallel projects employing the "new" and "old" methods are not very practical, either.

What we can say about the "success" of TQD is that:

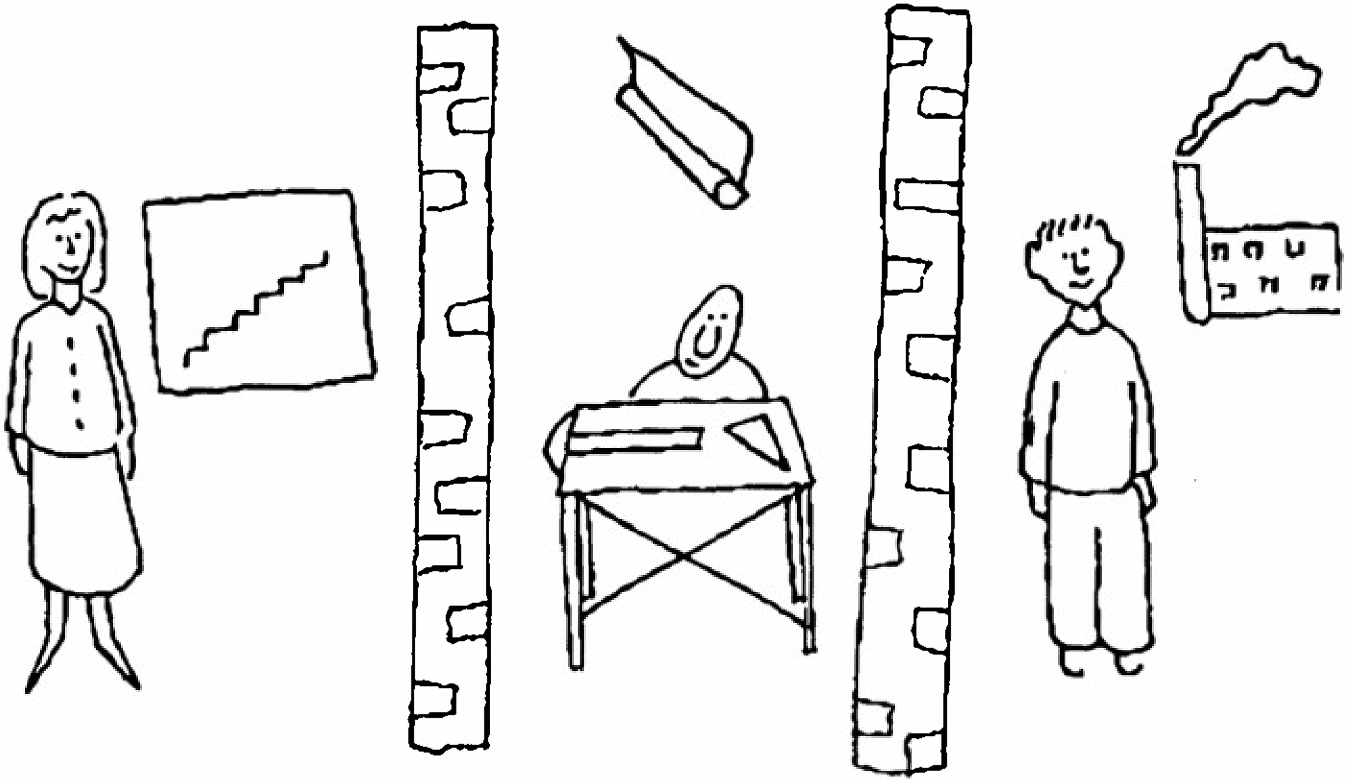
- Almost everyone, from student-engineers to senior administrators, who has learned the system has embraced it eagerly.
- The process does leave a "trail" that allows often highly conceptual decisions to be justified and explained with more than a "gut feel".
- Qualitatively, at least, many TQD teams believe that they have reduced the time to reach a first Go/No-Go decision for their project, while increasing the amount of information on which that decision is based.

I See and Forget, I Read and Understand, I Do and I Learn...

There is no substitute for experience when it comes to the TQD process. This process was built by trial and error, and it continues to evolve in the same way.

Some Final Words on "Concurrency"

Concurrent engineering is a vital element of TQD. As has been pointed out in several sections of this workbook there is a concurrency or trade-off factor among many of the fundamental TQD elements. For example, determination of the customers may cause the mission, or the team, to be modified. A second component of concurrency is related to the graphic below.



The graphic on the last page shows the famous "Wall" over which designs get thrown in corporate folklore.

Not surprisingly, the obliteration of this wall is a high priority of TQD. Thus, it must be emphasized that the eight elements of TQD do not represent a rigid, sequential, once-through process. This means, for example, that a team *can* discuss concepts while it is still trying to figure out who its customers are. In fact, such a discussion is likely to aid the process of customer determination.

TQD is what you make it.

To take this one step further, the TQD process can be thought of as a loose collection of the nine elements, which the team can reshape and rearrange to suit their purposes. Like any other set of heuristics, TQD should be used when it is useful, and modified or discarded when it is not.

The graphic on the last page shows the famous "Wall" over which designs get thrown in corporate folklore.

Not surprisingly, the obliteration of this wall is a high priority of TQD. Thus, it must be emphasized that the eight elements of TQD do not represent a rigid, sequential, once-through process. This means, for example, that a team can discuss concepts while it is still trying to figure out who its customers are. In fact, such a discussion is likely to aid the process of customer determination.

TQD is what you make it.

To take this one step further, the TQD process can be thought of as a loose collection of the nine elements, which the team can reshape and rearrange to suit their purposes. Like any other set of heuristics, TQD should be used when it is useful, and modified or discarded when it is not.

TQD continues to evolve.

Our TQD research attempts to ensure that TQD will remain useful. One of the most important elements in the continued improvement of TQD is *experience*. We are generating this experience internally, but the process will go much more quickly, with an attendant increase in the rate of improvement of TQD, if external TQD experience is related to us.

Please send us your comments, questions, and the results of your experiences!
Thanks...

John M. Henshaw
Mechanical Engineering Department
University of Tulsa
Tulsa, OK 74104-3189
(918)-631-3002

and

Dick J. Wilkins
Vistasp M. Karbhari
Center for Composite Materials
University of Delaware
Newark, DE 19716
(302) 451-8149

References

The "Vital Few":

The following references are gleaned from a very long list and offered as further reading for those interested in the Total Quality Design process:

Bebb, H. Barry, "Quality Design Engineering: The Missing Link to U.S. Competitiveness," Keynote Address, NSF Engineering Design Research Conference, Amherst, Massachusetts, June, 1989.

Clausing, Don P., "The Total Development Process: Turning the Ten Cash Drains into a Cash Flow," Unpublished work, 1988.

Cross, Nigel, *Engineering Design Methods*, John Wiley and Sons, 1989.

Edwards, Betty, *Drawing on the Right Side of Your Brain* and *Drawing on the Artist Within.*

Hauser, John, and Clausing, Don P., "The House of Quality," *Harvard Business Review*, May-June, 1988.

Henshaw, John M., *A Framework and Tools for the Early Decisions in the Product Development Process*, Ph.D. dissertation, University of Delaware, December, 1989.

King, Bob, *Better Designs in Half the Time*, GOAL/QPC, 1987

Pugh, Stuart, "Concept Selection: A Method that Works," ICED 81, Rome, 1981.

Koen, Billy V., *The Definition of the Engineering Method*, American Society of Engineering Education, Washington, 1985.

Taguchi, Genichi, *Quality Design Engineering*, Asian Productivity Organization, Tokyo, 1986.

Jacobson, Gary, and Hillkirk, John, *Xerox: American Samurai*, Macmillan, 1986.

APPENDIX 2

TQD USERS GUIDE

Appendix - TQD USER'S GUIDE (V2.3)

This User's Guide describes one common scenario for a TQD design project. Every project is different, of course, and the details will vary from one project to the next. This User's Guide is intended to help the beginning team master the "mechanics" of a TQD project, as opposed to the TQD Workbook, which introduces in detail the basic concepts of TQD. "Session" numbers listed below do not in most cases refer to the exact number of times your team will convene on a given project. Rather, these numbers represent logical breaks in the flow of a typical project.

The software described here requires Microsoft Excel Version 2.2.

Session 1

Once a team is selected, the first team meeting should be held in a room equipped for sharing the output of the Mac screen among the team. The Mac should be connected to a DataShow system and projected for team viewing.

Boot up TQD. Open "New Wants Table" from the menu (use ⌘-option-w). You will be asked to enter a name for the wants file being created. Use a name that includes "wants" and the current date. This spreadsheet, shown in Figure 1, is used to state the team's mission, and make a list of customers and wants. Develop a sharp, one-sentence statement of the mission of this TQD project or subproject. In making the customer list, use first and last names of real people whenever possible. Make a complete list of all possible ~~external~~ and internal customers. Consider converting internal customers into partners. In other words, get a buy-in from them to join the team as a member or consultant. Members are responsible for decisions, while consultants only provide information.

Once the first-pass list of customers is done, continue the session to brainstorm the wants of each customer, and enter the results as you go alongside each customers name. Duplications are fine. Just be as complete as possible. Conflicting wants are common, and are particularly useful to sharpen the decisions to be made. Continue to add wants, and even more customers until the team is satisfied. Consensus is sought for each team decision. Understanding the conflicting opinions is necessary. The team should have been selected for their expertise, and their willingness to exercise that expertise in decision making. Make the decisions and keep moving forward. Speed is especially useful early on. Iterations are expected and welcomed, but be aware of the trade-off with time. This should mark the end of the first TQD session. Save the spreadsheet. Make printouts for the team. Action items will probably include some customer contact (market research) to verify the team opinions expressed in the first spreadsheet. More sessions may be necessary to fill in the top customer wants and their rate of importance, which must be completed before proceeding to the next screen. (The Saaty method is being developed as a rigorous way to prioritize the wants.) Additional action items can be preparation of a list of competitors, along with information about their performance in each of the top customer wants.

Session 2

Session 2 is the beginning of the Competitive Benchmarking phase of the TQD process. Again boot up TQD. Open the customer wants file that you created in Session 1. Then open a metrics file by pressing option-command-m. Follow the on-screen instructions. Remember to use a name for the metrics file that includes the word "metrics" and the current date. The wants file that you will be asked for is the file created in Session 1. A blank version of the metrics template is shown in Figures 2,3, and 4. The mission statement and the top customer wants, along with their rates of importance, will be automatically imported from the wants screen. The first task for the team is to develop a numerical ranking to represent the current performance. Use a number between 1 and 5, with 5 as best. Next a listing of competitors is keyed in. It is especially good to include competitive entries that represent the best known performance in each of the separate customer wants. Continue the listing as long as necessary. Then rate the competitors against the customer wants. This may take outside homework and multiple sessions. Don't get stopped here. It is important for the team to exercise judgement so they can keep moving forward rapidly. After the competition is rated, one of the most important sets of decisions is considered. The team must select the ratings of the planned performance. This is based on careful considerations of the top customer wants, the current performance, the competitive performance, and the strategy for surpassing the competition. Once the planned performance ratings are completed, the software will calculate the ratio of improvement as the ratio of planned to current performance. The biggest changes will be given more weight later. The team then has the option of using "leverage" on one or more customer wants to put extra emphasis on it. As a first cut, insert "1" in each cell in the leverage row. The team may want to change the leverage in a successive TQD iteration.

The absolute weight is the product of the Rate of Importance times the Ratio of Improvement times the Leverage. The Demand Weight is the normalized weight as a percentage of the total of the absolute weights of all the top customer wants. This completes a very busy Session 2.

Save the changes. Make printouts for the team. Action items are to be thinking of quantifiable ways to measure each of the customer wants before the next session. Find out how the competitors measure themselves and how they advertise. Homework to verify the competitive benchmarking will almost always be welcomed, and will be a continuing process. Note that changes in the competitors ratings has no effect on the subsequent work, unless a change is needed in the Planned Performance. However, better homework on the competitors also pays off later when it is time for concept generation, as competitors' concepts should help your team generate new concepts.

Session 3

The next session begins by re-booting the TQD software and returning to the metrics file. Here, you will be using the center portion of the metrics template as shown in Figure 3. The first task is to brainstorm ways to measure the customer wants. Taking each customer want from top to bottom, consider all sorts of ways to measure that want. Key them into the spread sheet in arbitrary order, making a column of quality metrics. Try to think of at least 3 or 4 ways of measuring each want. Some metrics will be useful in measuring multiple wants. Use each such metric only once. Continue until consensus is reached or you run out of ideas. If necessary, take a break or end the session here, but try to continue.

The next task is to judge how strongly correlated each metric is to the customer wants. Taking each customer want in turn, mark the cells in each spreadsheet column according to the legend shown at the bottom of the center section of the template (Figure 3). Each mark corresponds to a multiplying factor as shown. In effect, the customer wants will be transformed into a set of measures that directly correlate with them. When the process is completed, the software will calculate the number of "points" associated with each metric. The one with the most points will be considered the most important metric. The original "Rate of Importance" of each want is taken into account in these calculations. Store that spreadsheet that contains the raw scores. Then modify the spreadsheet as follows. The Excel® program includes utilities for modifying the spreadsheets. Highlight Rows including all the quality metrics (all the way across). Pull down the Data menu to "Sort". Choose the column labeled "Pts" to sort by. Click descending, then click "OK".

The result will be a re-ordering of the quality metrics in order of number of points from top to bottom. The percentages are also shown. Save the spreadsheet under a different name. Now go through the metrics one-by-one to verify the interactions by row. See if they make sense. Later elements of the TQD process work best when the number of metrics is small, so try to cut the list down. Especially look at the bottom of the list to see if some of the lowest ones are covered by some higher ones. Sometimes you will be able to truncate the list at some obvious point below which the metrics have a very low rating. As the metrics are eliminated click on the row number of each metric to be eliminated and do a -K. If the calculation option is set on automatic, the percentages will be recomputed by the software itself. If the option is on manual, do a -= to re-calculate the percentages. If possible, eliminate metrics until the number of total metrics is less than 15 or so. But don't eliminate any metric that is strongly correlated to a want. When consensus is reached, go out and celebrate! You have reached a major milestone in the TQD process. You have developed an excellent team understanding of your customers, their wants, the competition, and how to measure the customer wants. Save the spreadsheet!

An additional step may be taken at this time to sharpen the team's understanding of what is required to beat the competition. Using the final portion of the metrics spreadsheet (Figure 4), the team can relate the quality metrics to the competition. This step will undoubtedly require some additional homework, but will also be quite valuable and in some cases critical. Find out what value of each metric corresponds to each competitor. Instead of relying on subjective ratings of the ability of each competitor to satisfy the customer as in the initial competitive benchmarking step, this evaluation will be based on actual performance to the metrics that have been identified as most important. This will force the team to re-think about how specifically the competition performs in the most important measurable ways. In addition, the team must include measures of their own current performance. Finally, the team can define the planned performance in terms of discrete, quantifiable metrics that have been derived to be the most important to the customers. These data are invaluable in the following steps to generate and select concepts. Save the spreadsheet for the next session. Make printouts for the team. Action items are to think about including "concepts" and features of concepts for satisfying the customer wants. Think about the best features of the competition. You must beat the competition in some way that strongly pleases the customer, but remember that you don't have to exceed or even equal the competition in all of the customer wants. In fact, it is wise to copy the competition in all wants that you can't beat. The motto is "If you can't beat it, use it!"

At this point, the team has come rapidly to the point of thoroughly understanding the customers, their wants, and the competition. If that was the only contribution of TQD, it would be totally worthwhile. But, the process flows smoothly onward to generate and select robust concepts to satisfy customer wants.

Session 4

The next session begins with the final template. From the TQD software, open a new concepts template with a command-option-c. A blank concepts template is shown in Figures 5 and 6. As before, the mission statement is included for constant reference. The benchmark refers to the incumbent or current concept. Quality metrics are automatically imported from the previous spreadsheet, in order of importance. (Planned values could also be included, but have not as yet. Other planned improvements include Taguchi's quality loss function to include manufacturing cost considerations at this early stage. The bottom portion of the template (Figure 6) will be utilized later in the concept selection process.)

At the top of the page is room to describe each concept. It is important to have an accompanying sketch of each concept. A future generation of TQD software will include links to concept sketches. Each concept should be described completely in terms of functionality. A component of a composite structure, for example, should be defined by its materials, configuration (shape and microstructure), and its manufacturing process. Heuristics maps for composites manufacturing, in terms of the most important process discriminators, are available in the Composites Manufacturing Heuristics Guide. The list of concepts can be as long as the team desires. It is extremely important to generate a relatively large number of concepts. Rows can be added to the spreadsheet if necessary. Each "concept" should be thought of as a complete answer to the customer wants, but the concepts list often becomes a list of features to be considered for inclusion. This part of the process is probably the most "creative", so constraints here are unwelcome. Let the ideas flow freely without criticism, in a classical brainstorming session. It may also be useful here to employ creativity software, such as IdeaFisher® to stimulate as many concepts as possible. At the end of this session, call for a break or quit. Save your work.

Session 5

When you re-convene, you will be entering one of the most powerful elements of the TQD process. The concept selection process, based on the Pugh method, ensures that only robust concepts are selected. It saves the team from taking risks on weak concepts.

When completed, this part enables the entire team to uniformly defend their decisions to each of their constituencies. It is the final step before the Go/No-Go Review.

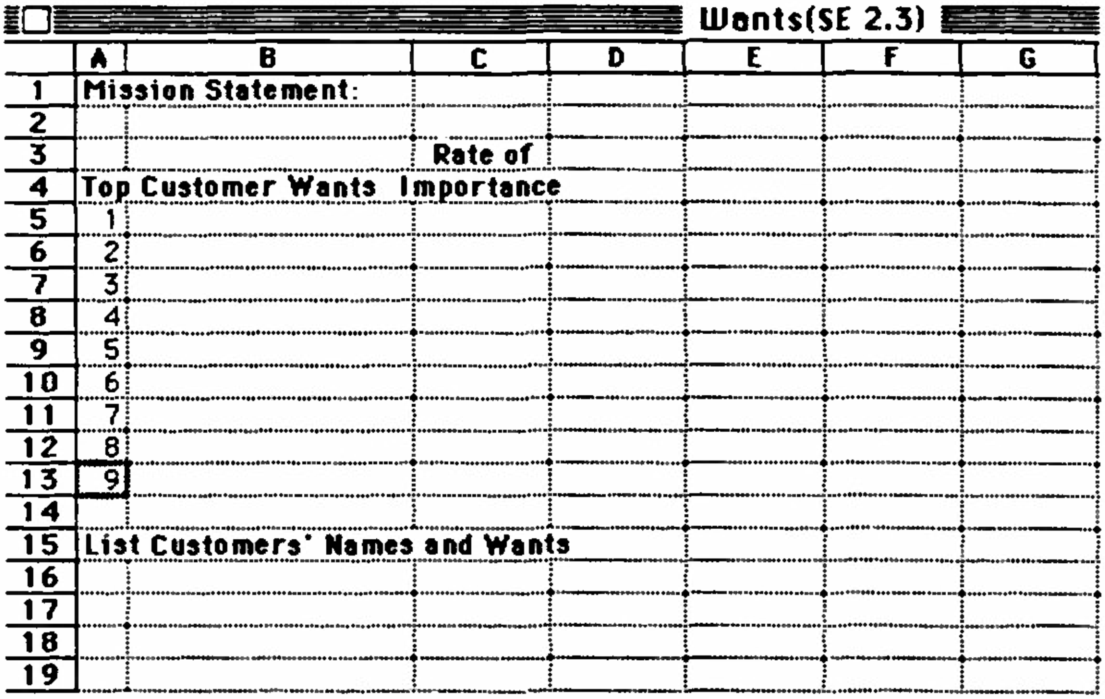
Start in the middle of the template with concept #1 and quality metric #1. Ask yourselves if concept #1 is better, worse, or the same as the benchmark in terms of quality metric number #1. Insert a "b" if it is better, a "w" if it is worse, or an "e" if it is the same/equal. If you don't know (i.e there exists a knowledge gap), put a "g". Continue to evaluate concept #1 against the benchmark by proceeding down the column marked concept #1. When you finish concept #1, do the same thing with concept #2 and so forth until you fill all cells of the spreadsheet. The software will sum up the number of each type of comparison (b, w, e, g) at the bottom of the template (Figure 6). This will also show various ways of evaluating the strength of each concept (i.e., "number of plusses", number of plusses + number of equals"). The row marked "Number of invalid entries" should be checked to ascertain that no letters other than "b", "w", "e" or "g" were entered in any of the columns.

Now comes some serious decision-making. Seek to eliminate weak concepts at this point. If a concept has so many minuses (w) that it would be weak even if all the knowledge gaps (g) were resolved, eliminate it. This shows the power of the process to save time by not spending resources on weak concepts. Many knowledge gaps will probably remain. Action items should be assigned to fill the most serious knowledge gaps. Take a look at the most attractive concept. During the next session, consider making that concept the benchmark. Proceed carefully to eliminate concepts and re-compare all remaining ones to the most likely winners. Add detail to the remaining concepts to be able to better differentiate them. Continue iterating and doing homework as necessary. Try hard to end up with one best concept to take to the Go/No-Go Review. (Save your work!)

Session 6

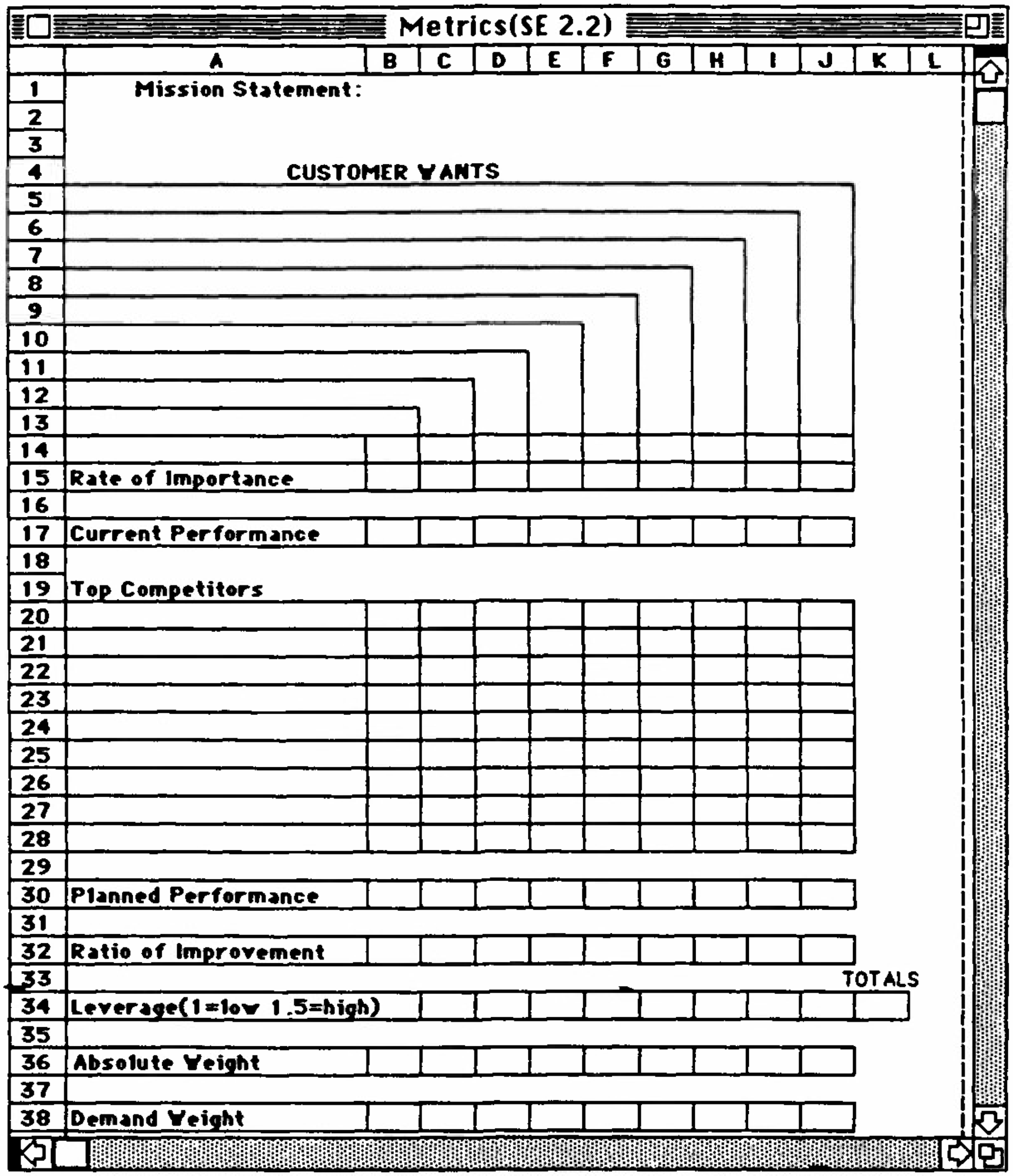
The Go/No-Go Review is the culmination of the TQD process for conceptual design. (TQD can, of course, also be used for detail design, process design, strategic planning, complex decision-making, etc.) The Go/No-Go Review allows the team to report back to management on the results of their TQD process. It employs the templates from a historical viewpoint to review each of the key decisions and allows the team to answer questions about the effort. Each key template is presented, either in hard copy or electronically, to guide the presentation. Key decisions are highlighted. Finally the team presents their conclusions. The best result is discovering a robust concept that has a good chance of beating the competition. A more likely result in many cases is a conclusion that the information and technology are not available from which to develop a way to beat the competition. The team can clearly articulate the reasons for not finding a concept robust enough for the organization to expend further resources on. The organization can then use the results to guide its R&D efforts, so that next time the information and technology will be available.

This TQD User's Guide has explained the steps and some of the philosophy of Total Quality Design. More detailed information on the background and philosophy are available in the TQD Workbook. TQD is an evolving process that thrives on examples and case studies. Please let us know what works and what doesn't work for you.



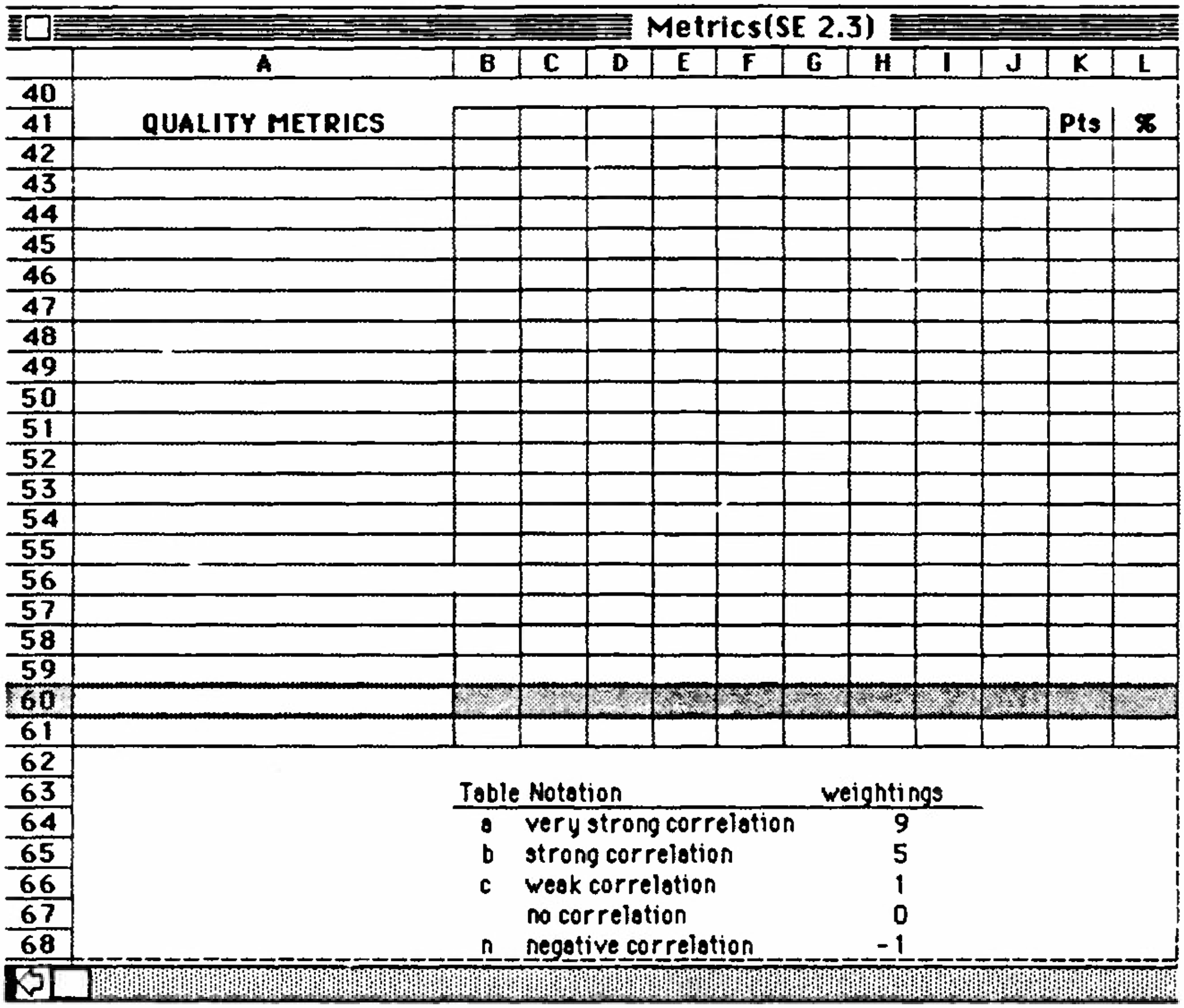
	A	B	C	D	E	F	G
1	Mission Statement:						
2							
3			Rate of				
4	Top Customer Wants		Importance				
5	1						
6	2						
7	3						
8	4						
9	5						
10	6						
11	7						
12	8						
13	9						
14							
15	List Customers' Names and Wants						
16							
17							
18							
19							

Figure 1 - The TQD "wants" template



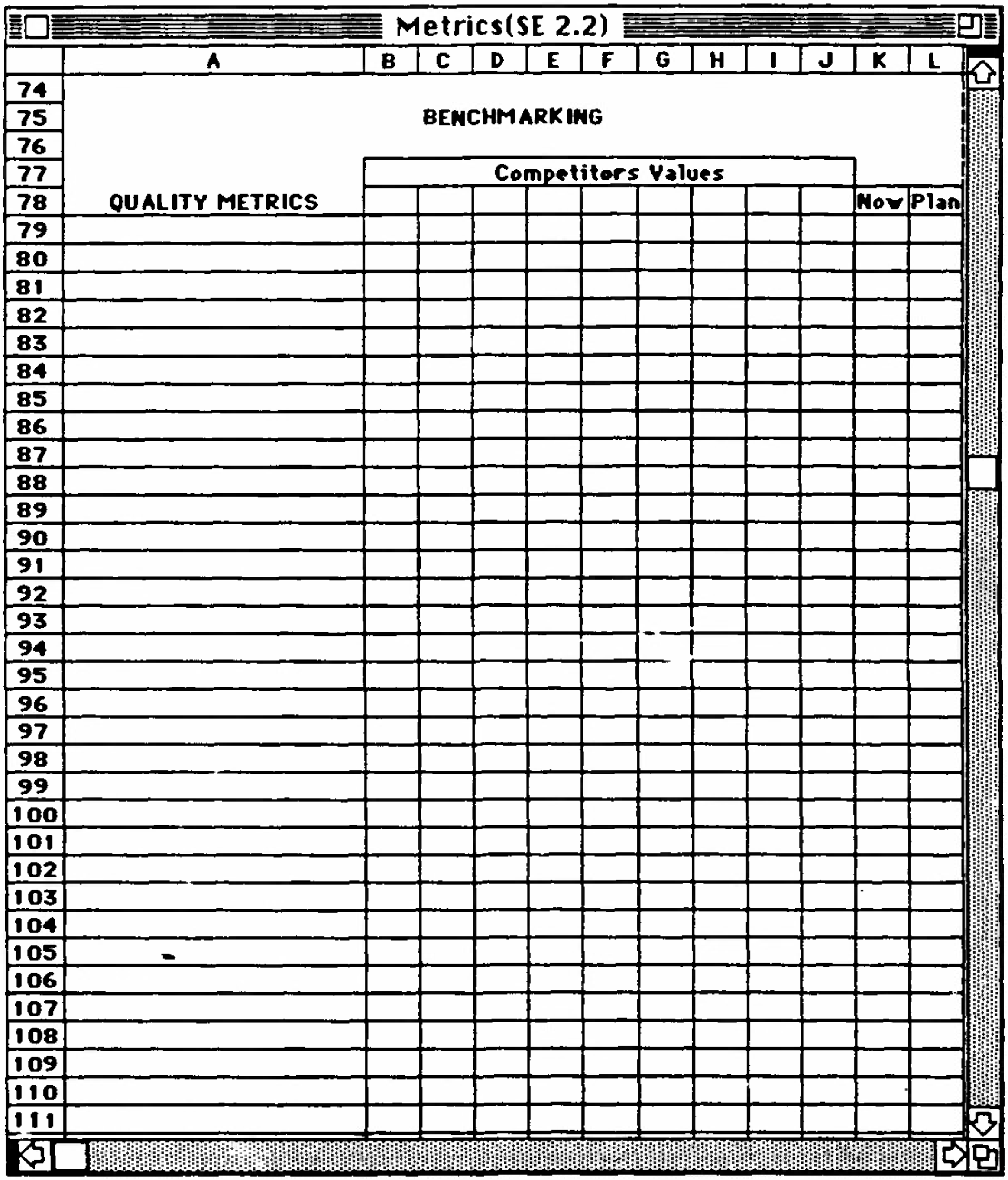
	A	B	C	D	E	F	G	H	I	J	K	L
1	Mission Statement:											
2												
3												
4	CUSTOMER WANTS											
5												
6												
7												
8												
9												
10												
11												
12												
13												
14												
15	Rate of Importance											
16												
17	Current Performance											
18												
19	Top Competitors											
20												
21												
22												
23												
24												
25												
26												
27												
28												
29												
30	Planned Performance											
31												
32	Ratio of Improvement											
33											TOTALS	
34	Leverage(1=low 1.5=high)											
35												
36	Absolute Weight											
37												
38	Demand Weight											

Figure 2 - TQD "quality metrics" template (top section)



	A	B	C	D	E	F	G	H	I	J	K	L
40												
41	QUALITY METRICS										Pts	%
42												
43												
44												
45												
46												
47												
48												
49												
50												
51												
52												
53												
54												
55												
56												
57												
58												
59												
60												
61												
62												
63		Table Notation					weightings					
64		a	very strong correlation					9				
65		b	strong correlation					5				
66		c	weak correlation					1				
67			no correlation					0				
68		n	negative correlation					-1				

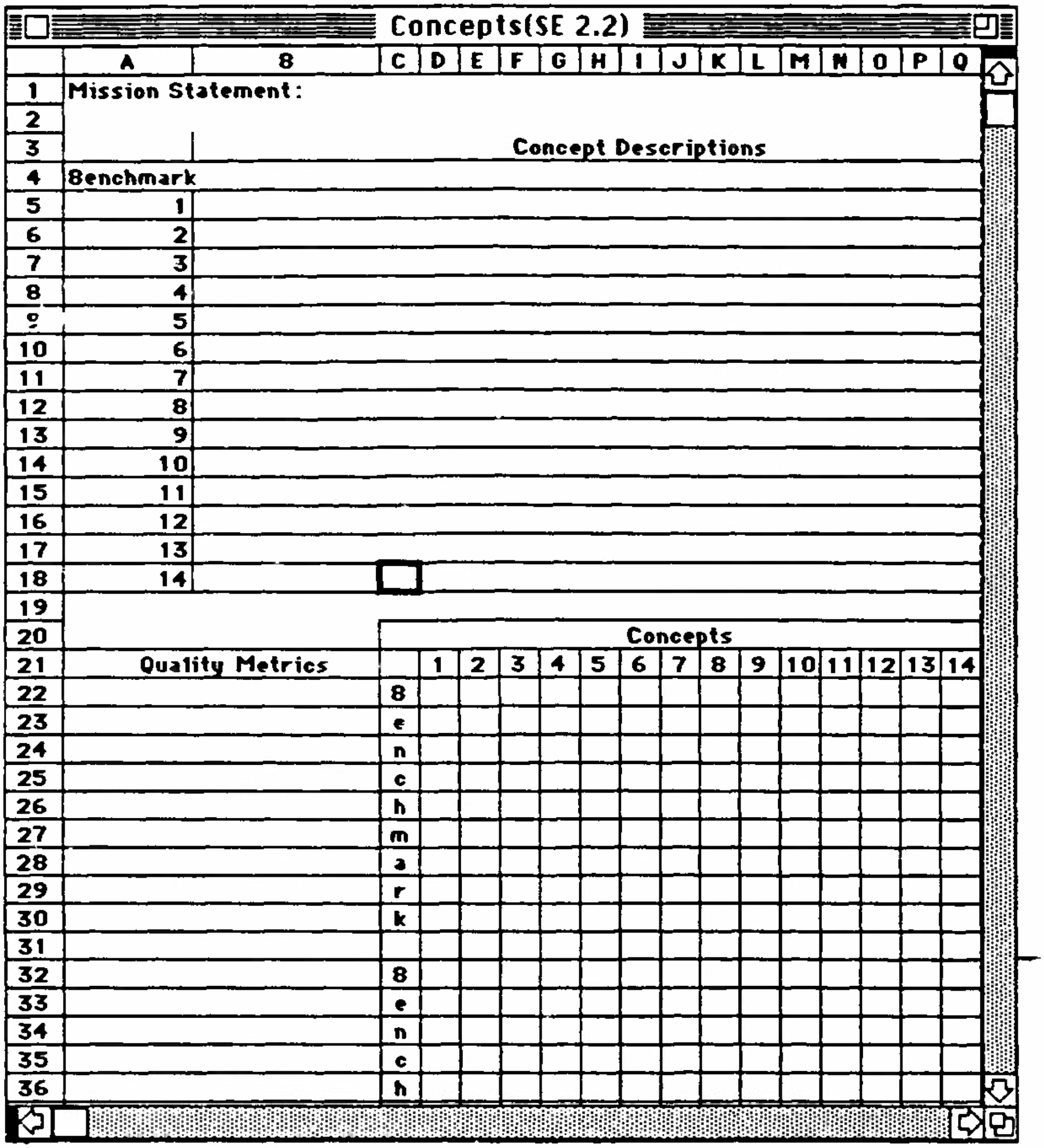
Figure 3 - TQD "quality metrics" template (center section)



Metrics(SE 2.2)

	A	B	C	D	E	F	G	H	I	J	K	L
74												
75					BENCHMARKING							
76												
77		Competitors Values										
78	QUALITY METRICS										Now	Plan
79												
80												
81												
82												
83												
84												
85												
86												
87												
88												
89												
90												
91												
92												
93												
94												
95												
96												
97												
98												
99												
100												
101												
102												
103												
104												
105												
106												
107												
108												
109												
110												
111												

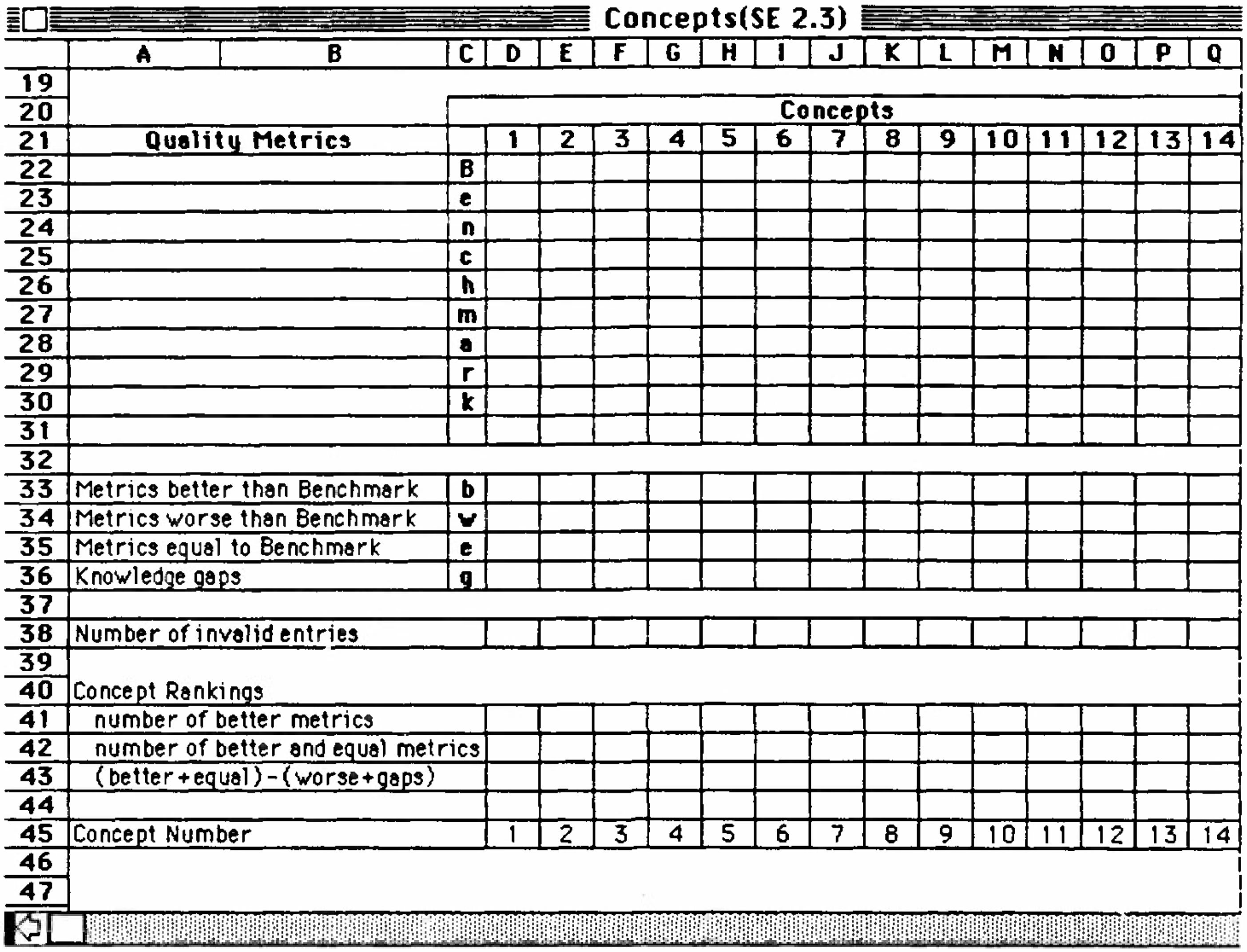
Figure 4 - TQD "quality metrics" template (bottom section)



Concepts(SE 2.2)

	A	8	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	Mission Statement:																
2																	
3		Concept Descriptions															
4	Benchmark																
5	1																
6	2																
7	3																
8	4																
9	5																
10	6																
11	7																
12	8																
13	9																
14	10																
15	11																
16	12																
17	13																
18	14																
19																	
20			Concepts														
21	Quality Metrics			1	2	3	4	5	6	7	8	9	10	11	12	13	14
22			8														
23			e														
24			n														
25			c														
26			h														
27			m														
28			a														
29			r														
30			k														
31																	
32			8														
33			e														
34			n														
35			c														
36			h														

Figure 5 - The TQD "concepts" template (top half)



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
19																	
20				Concepts													
21	Quality Metrics			1	2	3	4	5	6	7	8	9	10	11	12	13	14
22			B														
23			e														
24			n														
25			c														
26			h														
27			m														
28			a														
29			r														
30			k														
31																	
32																	
33	Metrics better than Benchmark		b														
34	Metrics worse than Benchmark		w														
35	Metrics equal to Benchmark		e														
36	Knowledge gaps		g														
37																	
38	Number of invalid entries																
39																	
40	Concept Rankings																
41	number of better metrics																
42	number of better and equal metrics																
43	(better+equal)-(worse+gaps)																
44																	
45	Concept Number			1	2	3	4	5	6	7	8	9	10	11	12	13	14
46																	
47																	

Figure 6 - The TQD “concepts” template (bottom half)

APPENDIX 3

LIST OF TECHNICAL PUBLICATIONS

V.M. Karbhari, J.M. Henshaw, D.J. Wilkins and S.H. Munson-McGee, *"Composites - Design, Manufacturing, and Other Issues: A View Towards the Future,"* to appear in the International Journal of Materials and Product Technology, Vol. 7, No. 1, 1992.

V.M. Karbhari and D.J. Wilkins, *“Metrics and scales of comparison - links between design and manufacturing of composites,”* to be published in the International Journal of Materials and Product Technology, Vol. 6, No. 4, 1991.

D.J. Wilkins and V.M. Karbhari, *"Concurrent Engineering for Composites,"* International Journal of Materials and Product Technology, Vol. 6, No. 3, 1991, pp. 257-268.

V.M. Karbhari, J.S. Burns and D.J. Wilkins, *"Total quality design : An approach for customer satisfaction in critical advanced technologies,"* submitted to Engineering Management Journal.

V.M. Karbhari and D.J. Wilkins *"The use of decision support systems for the concurrent engineering of composites,"* submitted to International Journal of Materials and Product Technology.

V.M. Karbhari, D.A. Steenkamer, D.J. Wilkins and J.M. Henshaw, *"Support Systems for Composites Product Development,"* Proceedings of the 23rd International SAMPE Technical Conference, October 1991, Lake Kiamesha, NY, pp. 313-325.

D.A. Steenkamer, D.J. Wilkins and V.M. Karbhari, *"Strategies for designing multi-element preforms for RTM,"* ibid, pp. 885-899.

S.G. Slotte, V.M. Karbhari and D.J. Wilkins, *"Effect of Fiber Architecture on Performance and Manufacturability of RTM Parts,"* ibid, pp. 900-912.

V.M. Karbhari, J.S. Burns and D.J. Wilkins, *"The Total Quality Design (TQD) Approach for Composites,"* pp.1097-1111.

D.A. Steenkamer, D.J. Wilkins, V.M. Karbhari, and S.G. Slotte, *“Preform Joining Technology Applied to a Complex RTM Structural Part,"* Proceedings of the ASM/ESD conference, Sept. 30-Oct. 3, Detroit, pp. 443-452.

V.M. Karbhari, S.G. Slotte, D.A. Steenkamer and D.J. Wilkins, *"Effect of Preform Architecture and Injection Strategies on the Robustness of RTM Parts,"* ibid, pp. 91-103.

V.M. Karbhari and D.J. Wilkins, *"Decision Support Systems for the Concurrent Engineering of Composites,"* ibid, pp. 459-467.

V.M. Karbhari, J.M. Henshaw and D.J. Wilkins, *"The Scale Concept in Design Integration for Composites,"* 36th International SAMPE symposium, April 1991, San Diego, California, pp. 705-718.