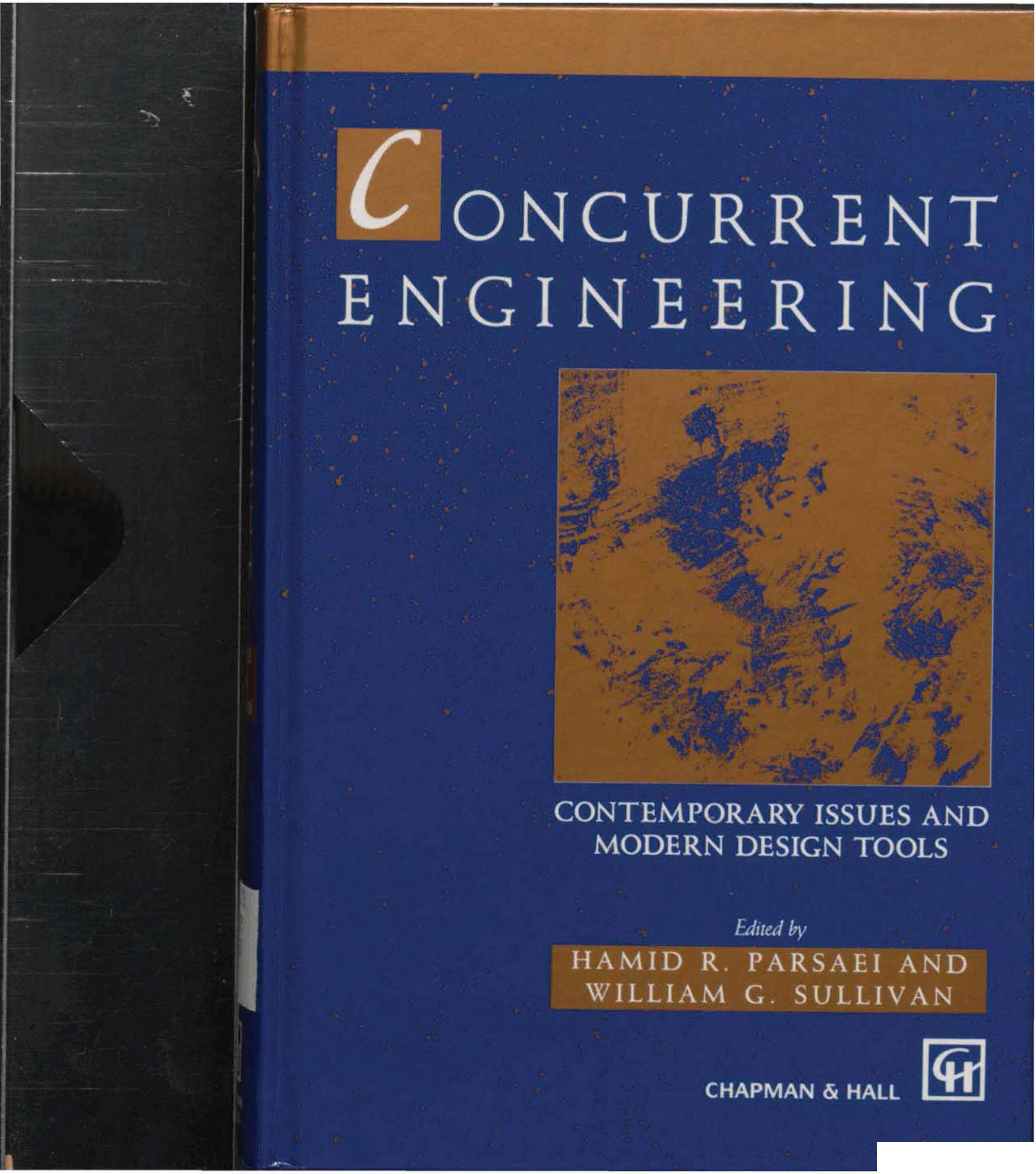

CONCURRENT ENGINEERING

CONTEMPORARY ISSUES AND MODERN DESIGN TOOLS

Edited by

HAMID R. PARSAEI AND
WILLIAM G. SULLIVAN

CHAPMAN & HALL

To our parents,
Abolfazl Parsaei and Barat Atabaki,
William H. Sullivan and Kathleen A. Glasstone

Concurrent Engineering

Contemporary issues and modern design tools

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Luckman, J. (1967) *Operational Research Quarterly*, **18**(4), 345–58.
Serbanati, L.D. (1987) *IEEE 9th International Conference of Software Engineering*, 190–7.
Simon, H.A. (1969) *The Science of the Artificial*, MIT Press, Cambridge, MA.
Suh, N.P., Bell, A.C. and Gossard, D.C. (1978) *Journal of Engineering for Industry Transactions of ASME*, **100**(2), 127–30.
Suh, N.P. (1984) *Robotics and Computer Integrated Manufacturing*, **1**(3/4), 399–455.
Suh, N.P. (1990) *The Principles of Design*, Oxford University Press, New York, Oxford.
Tyng, A. (1984) *Beginnings*, John Wiley & Son, New York.
Yoshikawa, H. and Warman, E.A. (eds) (1987) *Proceedings of the IFIP W.G.5.2 Working Conference 1985 (Tokyo)*, North-Holland, Amsterdam.

CHAPTER 8

A decision-based approach to concurrent design

Farrokh Mistree, Warren Smith and Bert Bras

Modern, computer-based concurrent design requires a holistic approach that integrates the representation, management and processing of information. Integration is possible through the 'standardization' of information management within a design process. We approach standardization from the perspective of decision-based design (DBD), namely, that 'the principal role of an engineer, in the design of an artifact, is to take decisions'. Given that decisions are foundational, we enable concurrent design processes through the simultaneous analysis, synthesis and resolution of multiple decisions.

In this chapter, we introduce the fundamental paradigms of DBD and describe a decision-based design methodology called the decision support problem technique (DSPT). Specifically, we start by providing some background and by stating the axioms needed to characterize 'decisions' as decision support problems (DSPs). Introduced next is the formal syntax and semantics of DSPs. This generic protocol ensures the applicability of the DSPT across varying domains of application by providing uniform and structured mappings between the designers' view of the world and the particular syntax needed to facilitate solution. Finally, we present some examples from marine design to explicate our approach.

8.1 SHIP DESIGN CASE STUDIES – NOMENCLATURE

Variables:

L	or LBP	length between perpendiculars in meters	
B	or BEAM	ship design beam in meters	
T	or DRAFT	ship design draft in meters	
D	or DEPTH	ship design depth in meters	
C_b	or CB	block coefficient (ship's hull)	$= \dfrac{\text{Displaced volume}}{L \times B \times T}$

C_p	or CP	prismatic coefficient (ship's hull)	$= \frac{\text{Displaced volume}}{\text{Midship section area} \times L}$
C_w	or CW	waterplane coefficient (ship's hull)	$= \frac{\text{Waterplane area}}{L \times B}$
LCB		longitudinal center of buoyancy in meters forward of midships	
LCF		longitudinal center of flotation in meters forward of midships	
SDKHT		standard height between decks in meters	
VK		maximum sustained speed in knots	
VKCR		endurance speed in knots	

Other parameters:

CODOG	combination of diesel engine (for VKCR) or gas turbine (for VK) – propulsion plant
CODAD	combination of diesel engine and gas turbine (for VKCR and VK) – propulsion plant
COGAG	combination of gas turbine and gas turbine (for VKCR and VK) – propulsion plant
GM	vertical distance between the center of gravity and the transverse metacenter
ROI	economic return on investment

8.2 OUR FRAME OF REFERENCE

It is our contention that to increase both the efficiency[1] and effectiveness[2] of the process of design a contemporary paradigm for design is needed. We offer such a paradigm from the perspective of decision-based design. The paradigm which encompasses systems thinking and embodies the ideas of concurrent engineering design for the life cycle is based on the foundational premise that 'the principal role of an engineer, in the design of an artifact, is to make decisions'. We demonstrate concurrency by the simultaneous solution of multiple decisions and through the integration and holistic treatment of design analysis and synthesis. By choice, we focus on the early stages of project initiation. This is not to say that the tools we develop and employ are limited to applications within the early stages. Our motivation to work in the early stages is that it offers the greatest potential to affect the design process and the artifact, since this phase dramatically shapes what is to follow.

As a design process progresses and decisions accumulate the freedom to make changes is reduced. At the same time, the knowledge about the object of design increases. This increase in knowledge is characterized by a transformation of 'soft' information into 'hard' information. By soft information, we refer to the heuristic and qualitative information that stems from a designer's judgment and experience whereas hard information tends to be based on scientific principles and to be more quantitative in nature. Given this nature of design information, what a concurrent design approach facilitates is 'to know' more about the design early on, that is, increase in qualitative ratio of hard to soft information. This relative improvement in the quality of information is expected to lead to equivalent or better designs that are completed in less time and at less cost than those designed using a traditional sequential process.

Compared to traditional engineering design in which synthesis of the product plays the central role, the dominant feature in concurrent engineering is the synthesis of the process (which includes design, manufacture and support aspects). With the synthesis of the process, it is expected that the synthesis of the product will follow naturally. Certainly some aspects of the design are by necessity pursued sequentially. For example, the preliminary design event will generally follow the conceptual design event. What we mean specifically by the synthesis of the process and concurrent design is that the decisions that can be simultaneously resolved are simultaneously resolved. Indeed, what we seek is a holistic integrated model that yields a solution to all of the relevant decisions simultaneously.

Given this argument and as evidenced by the host of design research initiatives being undertaken worldwide, design science is an emerging discipline and the attitudes toward design are changing. The fundamental reasons for this can be attributed to two singular events; a new emphasis on systems thinking and the pervasive presence of computers. However, independent of the approaches or methods used to plan, establish goals and model systems; designers are and will continue to be involved in two primary activities, namely, processing symbols and making decisions. So, what characterizes a decision?

The characteristics of decisions are governed by the characteristics of design of real-life engineering systems. These characteristics may, in part, be summarized by the following descriptive sentences:

- Decisions involve information that comes from different sources and disciplines;
- Decisions are governed by multiple measures of merit and performance;
- All the information required to make a decision may not be available;
- Some of the information used in making a decision may be hard and some information may be soft; and
- The problem for which a decision is being made is invariably loosely defined and open.

Virtually none of the decisions are characterized by a singular, unique solution. The decision solutions are less than optimal and are called satisficing solutions.

From a decision-based design perspective, decisions help bridge the gap between an idea and reality. They serve as markers and units of communication to identify the progression of a design from initiation through implementation to termination and they exhibit both domain-dependent and domain-independent features. Focusing upon decisions leads to a description of the design processes written in a common 'language' for teams from the various disciplines – a language useful in the process of designing. Our formal definition of the term designing is as follows (Kamal, *et al.*, 1987; Mistree *et al.*, 1989):

> Designing is a process of converting information that characterizes the needs and requirements for a product into knowledge about a product.

In this definition, we use the term product in its most general sense. We believe that perhaps the most significant design products are the design processes themselves.

8.3 THE DECISION SUPPORT PROBLEM TECHNIQUE

The implementation of decision-based design can take different forms. We call our approach the decision support problem technique (DSPT). It is being developed and implemented, at the University of Houston, to provide support for human judgment in designing systems. The DSPT consists of three principal components: a design philosophy rooted in systems thinking, an approach for identifying and formulating decision support problems (DSPs), and the supporting software, DSIDES. The DSPT comprises two phases, namely, a meta-design phase and a computer-based design phase.

> Meta-design is a metalevel process of designing systems that includes partitioning the system for function, partitioning the design process into a set of decisions and planning the sequence in which these decisions will be made.

For meta-design to represent dynamic partitioning and planning the connotation we place on meta is derived from the work of Klir (Klir, 1985). He states that meta can have three meanings:

- *after* – meta X occurs after X; thus X is a prerequisite of meta X;
- *change* – meta X indicates that X changes and is a general name of that change; and
- *above* – meta X is above (superior to) X in the sense that it is more highly organized, of a higher logical type or viewed from an enlarged perspective (transcending).

We have adopted this third meaning. This notion of higher has also been adopted by the computer scientists, for example, in terms like meta-knowledge, meta-domain, etc.

During Phase I (meta-design), the detailed product specific decisions are not made or even pursued. Rather, what is designed is the process to be implemented in Phase II. In Phase II (design), major decisions are modeled as DSPs and solutions to these DSPs are sought. Phase I of the DSPT is based on the primary axioms of DBD. These axioms map the particular design tasks to characteristic decisions and provide a domain-independent framework for the representation and processing of domain relevant design information (Kamal, 1990).

> Axiom–1 Existence of decisions in the DSPT
> The application of the DSPT results in the identification of decisions associated with the system (and subsystems that may be relevant).

> Axiom–2 Type of decisions in the DSPT
> All decisions identified in the DSPT are categorized as Selection, Compromise, or a combination of these.

Selection and compromise are referred to as primary decisions. All other decisions which are represented as a combination of these are identified as derived decisions. The selection decision, in the context of the DSPT, is defined as follows.

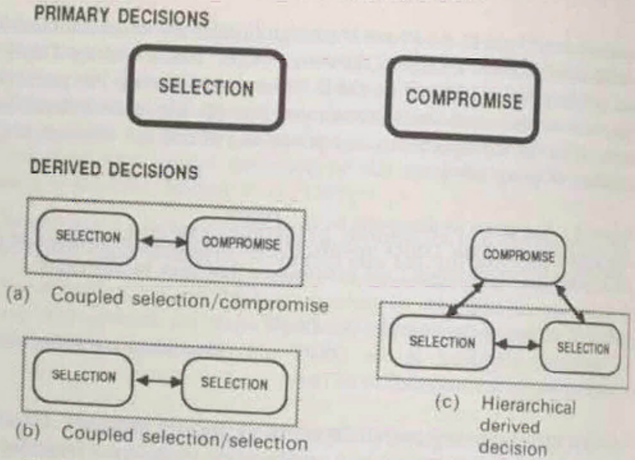
> Definition–1 The selection decision
> The selection decision is the process of making a choice between a number of possibilities taking into account a number of measures of merit or attributes.

The emphasis in selection is on the acceptance of certain alternatives through the rejection of others. The goal of selection in design is to reduce the alternatives to a realistic and manageable number based on different measures of merit. These measures, called attributes, represent the functional requirements and may not all be of equal importance. Some of the attributes may be quantified using hard information and others may be quantified using soft information. Similarly, the compromise decision, in the context of the DSPT, is defined as follows.

> Definition–2 The compromise decision
> The compromise decision requires that the 'right' values (or combination) of design variables be found to describe the best satisficing system design with respect to constraints and multiple goals.

The emphasis in compromise is on modification and change (e.g., dimensional synthesis) by making appropriate tradeoffs based on criteria relevant to the feasibility and performance of the system.

The second axiom is explained using set notation. The set of all primary decisions in the DSPT is given by, $Decision = \{S, C\}^3$ where S denotes Selection and C denotes Compromise. All derived decisions result from operations on this set. Some derived decisions are illustrated in Fig. 8.1. The coupled selection-compromise decision (Fig. 8.1a) is represented by the



(a) Coupled selection/compromise

(b) Coupled selection/selection

(c) Hierarchical derived decision

Fig. 8.1 Examples of derived decisions.

operator SC (S, C)[4] where S and C are contained in the set *Decision*. Similarly a coupled selection–selection decision (Fig. 8.1b) is represented by the operator SS(S, S). A hierarchical decision (Fig. 8.1c) is represented by CSS (C, SS(S, S)) where SS is as defined above. The efficacy of using coupled DSPs is discussed in (Karandikar, *et al.*, 1991; Karandikar and Mistree, 1992).

A corollary to Axiom–1 and Axiom–2 links the decisions to DSPs.

> Corollary to Axiom–1 and Axiom–2
> Decision support problems are utilized to provide decision support for the decisions identified (within the DSPT).

That is, decisions (primary and derived) are resolved using specialized constructs known as decision support problems. For instance, the coupled selection-compromise DSP is used to provide decision support for the decision shown in Fig. 8.1a. Within the DSPT the nature of decision support problems is qualified through the following two axioms (Kamal, 1990).

> Axiom–3 Domain independence of DSP descriptors and keywords
> The descriptors and keywords used to model DSPs need to be domain-independent with respect to processes (e.g., design, manufacture, maintenance) and disciplines (e.g., mechanics, engineering management).

> Axiom–4 Domain independence of the means to resolve DSPs
> The techniques used to resolve DSPs (to actually provide decision support) need to be domain-independent with respect to processes (e.g., design, manufacture, maintenance) and disciplines (e.g., mechanics, engineering management).

Summarized in Table 8.1 are the keywords and descriptors associated with the selection and compromise DSPs. The keywords are the 'verbs' that classify domain relevant information, and identify the relationships between that information. In the DSPs listed in Table 8.1, the keyword 'Given' is a heading under which the background or known information is grouped. Keywords embody in themselves the domain independent 'procedural knowledge'[5] for DSPs. Descriptors are objects organized under the relevant keywords within the DSP formulation. Again, they also help transform the problem from its discipline specific description to a discipline independent representation. For example, to select a material (using the selection DSP) based on strength, color and cost, the material choices are listed as 'alternatives' and the selection criteria as 'attributes'. Descriptors represent 'declarative knowledge'[6] (Rich, 1983).

Table 8.1 DSP keywords and descriptors

DSP	*Keywords*	*Descriptors*
Selection	Given	Candidate alternatives
	Identify	Attributes
		Relative importance
	Rate	Alternatives w.r.t. attributes
	Rank	Order of preference
Compromise	Given	Information
	Find	System variables
		Deviation variables
	Satisfy	System constraints
		System goals
		Bounds
	Minimize	Deviation function

Axiom–4 may seem self-evident as many solution techniques (e.g., linear programming, nonlinear optimization and expert systems) are applicable to problems from different domains. However, this condition supplements Axiom–3 by stating that decision support models using domain-independent constructs should be solved in a domain-independent manner.

To facilitate the design of engineering systems, our approach is to make available tools (analogous to the palette of a painter) that a human designer can use in various events of the design timeline. The decision support problem technique palette was first published in (Mistree *et al.*, 1990). Some refinement and expansion of the concept occurred and the current palette is fully described in (Bras and Mistree, 1991). The palette contains three different classes of entities, namely, potential support problem entities, base entities and transmission entities. The icons representing these entities are shown in Fig. 8.2. A model or network of a process is created by connecting entities in a systematic fashion. An extensive

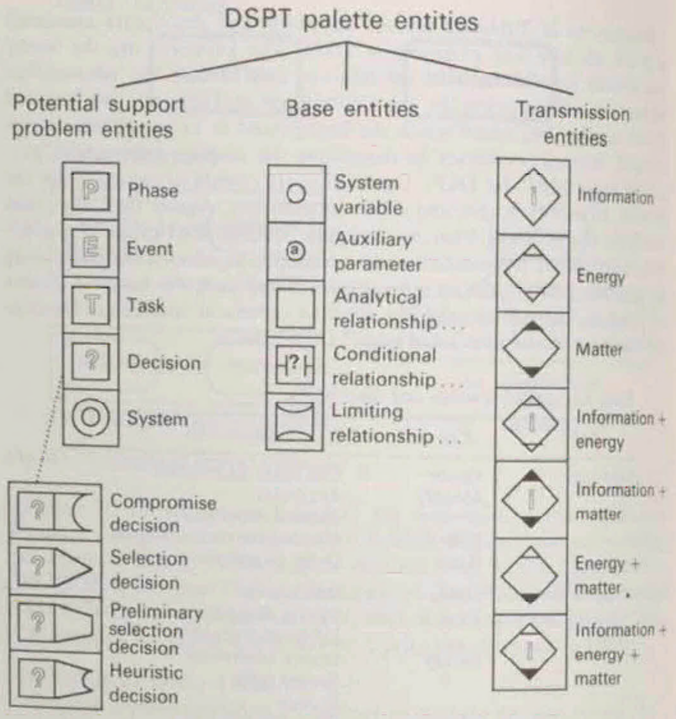


Fig. 8.2 The DSPT palette for modeling processes (Bras and Mistree, 1991).

example using the palette in the design of a frigate is given in (Mistree, et al. 1990).

A designer working within the DSPT has the freedom to use submodels or subnetworks of a design process created and stored by others (prescriptive models) and/or to create original models of the intended plan of action (descriptive models). The icons can easily accommodate different traditions and cultures and should not be considered limited to the examples presented herein. Further issues associated with designing models of design processes are discussed in (Bras *et al.*, 1990).

In Phase II of the DSPT, the focus is on structuring and solving the DSPs that correspond to the decisions identified in Phase I. The organization of information with keywords and descriptors results in a general knowledge representation scheme with an associated sense of data abstraction. Using the keywords and descriptors from Table 8.1, the selection DSP is reiterated as follows.

Given
A set of candidate alternatives.
Identify
The principal attributes influencing selection.
The relative importance of attributes.
Rate
The alternatives with respect to their attributes.
Rank
The alternatives in order of preference based on the computed merit function values.

Similarly, the compromise DSP is stated in words as follows:

Given
An alternative to be improved through modification.
Assumptions used to model the domain of interest.
The system parameters (fixed variables).
The constraints and goals for the design.
Find
The independent system variables values (they describe the artifact's physical attributes).
The deviation variables values (they indicate the extent to which the goals are achieved).
Satisfy
The system constraints that must be satisfied for the solution to be feasible.
The system goals that must achieve, to the extent possible, a specified target value.
The lower and upper bounds on the system variables and bounds on the deviation variables.
Minimize
The deviation function that is a measure of the deviation of the system performance from that implied by the set of goals and their associated priority levels or relative weights.

Since the selection DSP can be reformulated as a compromise DSP, the compromise DSP is considered the principal mathematical DSPT formulation (Bascaran *et al.*, 1989). This transformation of selection to compromise makes it possible to formulate and solve coupled selection–selection DSPs and coupled selection–compromise DSPs (Smith, *et al.*, 1987; Karandikar, 1989; Bascaran, 1990). Indeed, an augmented compromise DSP is used to solve any derived decision. Therefore, let us examine the underpinnings for the mathematical formulation of the compromise DSP.

The compromise DSP formulation is a multiobjective programming model which we consider to be a hybrid formulation (Mistree *et al.*, 1992). It incorporates concepts from both traditional mathematical programming and goal programming. It also makes use of some new features. The term 'Goal programming' was used, by its developers (Ignizio, 1982, 1983, 1985), to indicate the search for an 'optimal' program (i.e., a set of policies to be implemented), for a mathematical model that is composed solely of goals. This does not represent a limitation as any mathematical programming model (e.g., linear programming), may find an alternate representation via GP. Not only does GP provide an alternative representation, it often provides a representation that is more effective in capturing the nature of real world problems.

The compromise DSP is similar to GP in that the multiple objectives are formulated as system goals (involving both system and deviation variables) and the deviation function is solely a function of the goal deviation variables. This is in contrast to traditional mathematical programming where multiple objectives are modeled as a weighted function of the system variables only. The concept of system constraints is retained from the traditional constrained optimization formulation. However, the compromise DSP places special emphasis on the bounds of the system variables unlike traditional mathematical programming and GP. The compromise DSP constraints and bounds are handled separately from the system goals, contrary to the GP formulation in which everything is converted into goals. In the compromise formulation, the set of system constraints and bounds define the feasible design space and the set of system goals define the aspiration space (see Fig. 8.3). For feasibility the system constraints and bounds must be satisfied. A satisficing solution then is that feasible point which achieves the system goals as far as possible. The solution to this problem represents a tradeoff between that which is desired (as modeled by the aspiration space) and that which can be achieved (as modeled by the design space).

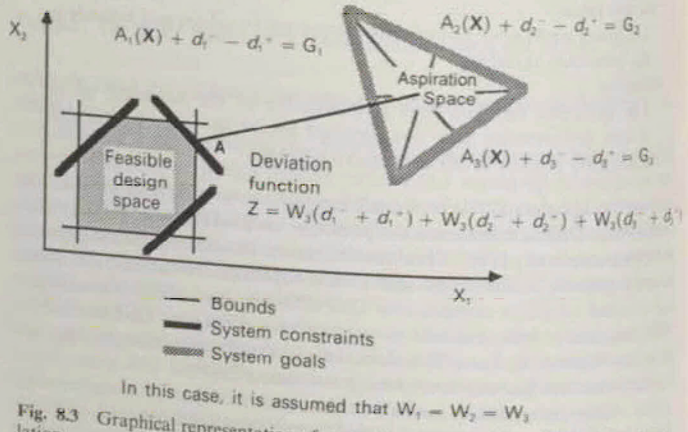


Fig. 8.3 Graphical representation of a two-dimensional DSP, Archimedean formulation.

Compromise DSPs are written, in general, in terms of *n* system variables. The vector of variables, **X** may include continuous variables and boolean (1 if TRUE, 0 if FALSE) variables. System variables are independent of the other descriptors and can be changed to alter the state of the system. System variables that define the physical attributes of an artifact must be positive.

A system constraint models a limit that is placed on the design. The set of system constraints must be satisfied for the feasibility of the design. Mathematically, system constraints are functions of system variables only. They are rigid and no violations are allowed. They relate the demand placed on the system, D(**X**), to the capability of the system, C(**X**). The set of system constraints may be a mix of linear and nonlinear functions. In engineering problems the system constraints are invariably inequalities. However, occasions requiring equality system constraints may arise. The region of feasibility defined by the system constraints is called the feasible design space.

A set of system goals is used to model the aspiration a designer has for the design. It relates the goal, G_i, of the designer to the actual performance, $A_i(\mathbf{X})$, of the system with respect to the goal. The deviation variable is introduced as a measure of achievement since we would like the value of $A_i(\mathbf{X})$ to equal G_i. Constraining the deviation variables to be non-negative, the system goal becomes:

$$A_i(\mathbf{X}) + d_i^- - d_i^+ = G_i;\ i = 1, \ldots, m$$

where

$$d_i^- \cdot d_i^+ = 0 \text{ and } d_i^-, d_i^+ \geqslant 0.$$

The product constraint ($d_i^- \cdot d_i^+ = 0$) ensures that at least one of the deviation variables for a particular goal will always be zero. If the problem is solved using a vertex solution scheme as a matter of course then this condition is automatically satisfied.

Bounds are specific limits placed on the magnitude of each of the system and deviation variables. Each variable has associated with it a lower and an upper bound. Bounds are important for modeling real-world problems because they provide a means to include the experience-based judgment of a designer in the mathematical formulation.

In the compromise DSP formulation the aim is to minimize the difference between that which is desired and that which can be achieved. This is done by minimizing the deviation function, $Z(d^-, d^+)$. This function is always written in terms of the deviation variables. All goals may not be equally important to a designer and the formulations are classified as Archimedean or Preemptive – based on the manner in which importance is assigned to satisficing the goals. The most general form of the deviation function for *m* goals in the Archimedean formulation is

$$Z(d^-, d^+) = \sum_{i=1}^{m} (W_i^- d_i^- + W_i^+ d_i^+)$$

where the weights $W_1^-, W_1^+, W_2^-, W_2^+, \ldots, W_m^-, W_m^+$ reflect the level of desire to achieve each of the goals. Generally, these weights would be chosen to sum to unity. However, it may be difficult to identify truly credible weights. A systematic approach for determining reasonable weights is to use the schemes presented in (Kuppuraju *et al.*, 1985; Bascaran *et al.*, 1989).

The most general approach to assigning priority is a preemptive one where the goals are rank ordered. Multiple goals can be assigned the same rank or level, in which case, Archimedean styled weights may be used within a level. This assignment of priority is probably easier in an industrial environment or in the earlier stages of design. The measure of achievement is then obtained in terms of the lexicographic minimization of an ordered set of goal deviations. Ranked lexicographically, an attempt is made to achieve a more important goal (or set of goals) before other goals are considered. The mathematical definition of lexicographic minimum follows (Ignizio, 1982, 1983).

> Lexicographic minimum
> Given an ordered array f of non-negative elements f_k's, the solution given by $f^{(1)}$is preferred to $f^{(2)}$ if $f_k^{(1)} < f_k^{(2)}$ and all higher-order elements (i.e., $f_1, \ldots, f_{k-1}$) are equal. If no other solution is preferred to f, then f is the lexicographic minimum.

If we consider $f^{(r)}$ and $f^{(s)}$, where $f^{(r)} = (0, 10, 400, 56)$ and $f^{(s)} = (0, 11, 12, 20)$, then $f^{(r)}$ is preferred to $f^{(s)}$. Hence, the deviation function for the preemptive formulation is written as

$$Z = \{f_1(d_i^-, d_i^+), \ldots, f_k(d_i^-, d_i^+)\}.$$

For a four goal problem, the deviation function may look like

$$Z(d^-, d^+) = \{(d_1^- + d_2^-), (d_3^-), (d_4^+)\}.$$

The numerical solution of a preemptive formulation requires the use of a special optimization algorithm developed to solve this type of problem. One such algorithm, Multiplex, has been developed by Ignizio (1985) and has been incorporated into DSIDES.

The Mathematical Formulation of the Compromise DSP is as follows:

Given

n	number of system variables
$p+q$	number of system constraints
p	equality constraints
q	inequality constraints
m	number of system goals
$g_i(\mathbf{X})$	system constraint function $g_i(\mathbf{X}) = C_i(\mathbf{X}) - D_i(\mathbf{X})$
$f_k(d_i)$	function of deviation variables to be minimized at priority level k for preemptive case
W_i	weight for Archimedean case

Find

System variables

$$X_i \qquad i = 1, \ldots, n$$

Deviation variables

$$d_i^-, d_i^+ \qquad i = 1, \ldots, m$$

Satisfy

System constraints (linear, nonlinear)

$$g_i(\mathbf{X}) = 0; \qquad i = 1, \ldots, p$$
$$g_i(\mathbf{X}) \geqslant 0 \qquad i = p+1, \ldots, p+q$$

System goals (linear, nonlinear)

$$A_i(\mathbf{X}) + d_i^- - d_i^+ = G_i; \quad i = 1, \ldots, m$$

Bounds

$$X_i^{\min} \leqslant X_i \leqslant X_i^{\max}; \qquad i = 1, \ldots, n$$
$$d_i^-, d_i^+ \geqslant 0; \qquad i = 1, \ldots, m$$
$$(d_i^-, d_i^+ = 0; \qquad i = 1, \ldots, m)$$

Minimize

Case a: Preemptive (lexicographic minimum)

$$Z = \{f_1(d_i^-, d_i^+), \ldots, f_k(d_i^-, d_i^+)\}$$

Case b: Archimedean

$$Z = \sum_{i=1}^{m} (W_i^- d_i^- + W_i^+ d_i^+)$$

As identified above, the selection DSP can be reformulated as a compromise DSP as follows:

Given

M	candidate alternatives
N	attributes
I_j	relative importance of the jth attribute
R_{ij}	the normalized rating of the ith alternative with respect to the jth attribute

$$\sum_{j=1}^{N} I_j R_{ij} = MF_i = \text{merit function of alternative } i$$

Find

Design variables

$$X_i; \quad i = 1, \ldots, M$$

Deviation variables

$$e^-, e^+$$

Satisfy

Selection system constraint

$$\sum_{i=1}^{M} X_i = 1 \tag{1}$$

Selection system goal

$$\sum_{i=1}^{M} MF_i X_i + \theta^- - \theta^+ = 1 \tag{2}$$

Bounds

$$0 \leqslant X_i \leqslant 1; \quad i = 1, \ldots, M$$

Minimize

$$Z = e^- + e^+$$

The solution to the 'reformulated' selection DSP which is a linear, 0–1 variable optimization problem can be found without necessitating the use of specialized integer programming codes. We use the ALP algorithm incorporated in DSIDES (Mistree *et al.*, 1981; Mistree *et al.*, 1992). In respect to the guaranteed boolean behavior of **X** for a single selection DSP, Bascaran (Bascaran *et al.*, 1989) argued the case in the following way. Considering the constraint that the product of e^- and e^+ is equal to zero, there are three equality equations in $M+2$ unknowns ($\mathbf{X}_{i-}$, for $i = 1, \ldots$ m M; e^- and e^+). By assuming normalization of the merit function values, that X_k is not perfect ($MF_k \neq 1$), and that the maximum merit function value is unique and nonzero ($MF_k > MF_i$ for all $i \neq k$); the equation for the product of the deviation variables leads to e^+ being zero, equation (2) leads to e^- being nonzero, and equation (1) to only one X_i being nonzero. The value of the nonzero X_i will then be unity as dictated by equation (1). A rigorous proof can also be provided using monotonicity analysis.

With care, this argument to guarantee boolean behaviour of continuous variables and uniqueness can be extended to coupled multiple-selection problems. For each selection problem, a particular uniqueness condition and a corresponding goal will exist in the formulation. However, a heuristic adjustment of the goals is recommended to ensure that e^- remains nonzero. Depending on the selection goal priorities and the right hand side (RHS) values of the goals, it is otherwise possible to satisfy the uniqueness constraints with a fractional, nonboolean **X** vector. The suggested adjustment to equation (2) is in a new RHS such as

$$\sum_{i=1}^{M} MF_i X_i + e^- - e^+ = M + \text{delta}.$$

When dealing computationally with complex coupled problems, additional system constraints and techniques may be helpful and/or necessary depending on the user's problem formulation. Indeed, an optional branch-and-bound zero-one algorithm is available within DSIDES for use with specially defined 'selection' variables. Alternatively, if a designer wishes to use continuous variables exclusively and to impose boolean behavior, constraints such as

$$\sum_{i=1}^{M} X_i(1 - X_i) = 0$$

are strongly recommended. This modification has proved useful in practice.

Additional system constraints may be required to model exclusionary behavior. For example, certain combinations of alternatives in a coupled selecting–selection DSP may be infeasible. Consider the case where if material A is selected ($X_1 = 1$), manufacturing process C cannot be used ($X_7 \neq 1$). This condition can be modeled as

$$X_1 + X_7 \leqslant 1.$$

The use and formulation of such exclusionary constraints is demonstrated in (Karandikar, 1989; Bascaran, 1990).

As a final word here on selection, while an engineering solution can be sought in this way, the designer must examine the sensitivity of the information used. The variances of the rating (or grading) systems used may in reality be too great to truly discriminate one solution from another. (Remember that the goal of the DSPT is to provide decision support and not to automate the decision process). For further details regarding this issue, (see Kuppuraju *et al.*, 1985; Bascaran *et al.*, 1989).

As stated earlier, in our case, concurrent design is achieved within a decision or subsystem through the integration and holistic treatment of design analysis and synthesis. Further, concurrency is modeled by the simultaneous consideration of subsystems, or in DBD terms, the simultaneous resolution of derived decisions. Consider a derived decision involving two compromise DSPs and one selection DSP. Some characteristics of concurrent design are embodied in the system synthesis, a mathematical formulation of which is provided in Table 8.2. Each subsystem is shown to impact the others through the subsystem constraints and goals being functions of all of the subsystem variables. Concurrency is also emphasized in the minimization of a composite deviation function.

8.4 APPLICATIONS OF THE DECISION SUPPORT PROBLEM TECHNIQUE

Applications of DSPs include the design of ships, damage tolerant structural and mechanical systems, the design of aircraft, mechanism, thermal

Table 8.2 Modeling concurrency through system synthesis–succinct math formulation

Compromise DSP 1	Compromise DSP 2	Selection DSP
Find		
$\mathbf{X}, d^-, d^+$	$\mathbf{Y}, e^-, e^+$	$\mathbf{S}, h^-, h^+$
Satisfy		
$g_i(\mathbf{X}, \mathbf{Y}, \mathbf{S}) \geqslant 0$	$g_i(\mathbf{X}, \mathbf{Y}, \mathbf{S}) \geqslant 0$	$\sum S_i = 1$
$A_i(\mathbf{X}, \mathbf{Y}, \mathbf{S}) + d_i^- - d_i^+ = G_i$	$A_i(\mathbf{X}, \mathbf{Y}, \mathbf{S}) + e_i^- - e_i^+ = G_i$	$\sum MF_i(\mathbf{X}, \mathbf{Y})S_i + h^- - h^+ = 1$
$X_i^{min} \leqslant X_i \leqslant X_i^{max}$	$Y_i^{min} \leqslant Y_i \leqslant Y_i^{max}$	$0 \leqslant S_i \leqslant 1$
$d^-, d^+ \geqslant 0$	$e^-, e^+ \geqslant 0$	$h^-, h^+ \geqslant 0$

Minimize (lexicographically)

$$Z = \{h^-, f_1(d^-, d^+, e^-, e^+), \ldots, f_k(d^-, d^+, e^-, e^+)\}$$

Notes:
X, Y – system variables
S – selection variables
$d^-, d^+, e^-, e^+, h^-, h^+$ – deviation variables
g_i–ith constraint function for subsystem
A_i – ith goal function for subsystem
G_i – ith goal target value for subsystem
MF_i – ith merit function for alternative s_i
Z – deviation function (Preemptive form, k priority levels)

energy systems, design using composite materials and data compression. A detailed set of references to these applications is presented in (Mistree *et al.*, 1990). However, in the following sections, a collection of representative examples from the marine field are presented. They are based on a general analysis of current practice, but no attempt is made to constrain all design life cycles to fit these models. For the examples, a conscious decision has been made not to document one design problem from beginning to end. Rather, to emphasize the versatility of the approach, a number of problems are partially addressed. These examples highlight aspects such as meta-design, the representation of ship subsystems as DSPs, design synthesis, possible results and the parametric use of results. Collectively, the examples are used to illustrate the efficacy of the DSPT in supporting a human designer. To aid understanding, the examples are provided in a pseudo-chronological form in keeping with the two phases of the DSPT.

Experience indicates practical success in using DSPs to solve ship design problems. In addition to the studies discussed herein, five case studies involving comparisons of preliminary ship designs developed using RAPID (a DSIDES template[7]) with designs produced commercially are detailed in (Lyon and Mistree, 1985). The first two case studies involve actual proven designs that RAPID matched in all technical aspects. The remaining three case studies represent comparisons with other computer-assisted ship design methods. In these cases, RAPID designs were considered superior overall, both in approach and results.

8.4.1 A meta-design example: modeling the process of design

As a representation of meta-design at the highest level, a portion of a hypothetical timeline for designing a frigate is shown in Fig. 8.4. This is referred to as the phase-event-information diagram or the P-E-I diagram for short. From left to right, the qualitative relationship between hard and soft information increases. The design phases, events and product specific information are shown in different sections within the figure. The storybook graphics at the top represent the strategic need, the various concepts, the selected basic concept, the preliminary design, the contract negotiations, the manufacturing, the finished ship, the ship after the half-life refit and the decommissioned ship.

The timeline is partitioned into four major design phases for this example. Typically, the end of each phase is not abrupt and it is often difficult to see when a new phase starts. Therefore, the phases in Fig. 8.4 overlap each other. Within these phases we identify a number of events. Events are not restricted to one phase. For instance, the preliminary design event is found in designing for concept, designing for manufacture and designing for maintenance. The horizontal bars provide an indication of the duration, in physical time, of phases and events. Input to the design process is a strategic need or foreign policy and during the life of the frigate more and more hard information becomes available (e.g., drawings and documentation). Thus, the ratio of hard to soft information is seen to increase as the timeline is traversed from left to right.

The output of each event augments the product specific information. This is shown in the fourth section of Fig. 8.4. The first event identified is the development of the Naval Staff requirements. This event results in a significant document referred to as the 'Statement of requirements'. This document plus general design information then forms the primary input for the conceptual design event. The conceptual design event feeds forward a basic concept while initiating a feedback loop to the development of the naval staff requirement event. The basic concept and the general design knowledge provide the necessary information for the preliminary and contract design events. Note that again an overlap between these two events occurs. The preliminary design event provides the top level specification and the ship characteristics, whereas the contract design event provides the general specification and the guidance drawings.

As stated, the output of each event augments the product specific information. This is useful in planning a project. A designer of the design process could ask the following question: If I had some particular information, will I be able to use it to further my design? If the answer is yes it may be entered in the product specification line. Of course there are other questions that this designer will pose and answer before arriving at the correct statement of the product specification section. Some examples: Can I obtain this information in some easier manner? What are the consequences of my forgoing this information? In summary, the P-E-I diagram provides a good foundation for developing design process schedules and barcharts.

While a concurrent approach in respect to model synthesis is ideal in all design phases and there is a similarity in the decision templates across the timeline of a design, one 'super' template cannot model all phases effectively. What is sought is the development of phase and event based 'master derived decision templates' that account for, at an appropriate level, as many aspects of the design life-cycle as is possible and/or reasonable. For a closer look at the preliminary design event of Fig. 8.4, imagine 'double clicking' on the event bar chart on the preliminary design bar. 'Opened' as the subordinate layer of process documentation would be the model of this event as shown in Fig. 8.5. The master decision template is the 'preliminary ship synthesis' entity at the center, shown under the magnifying glass. All other activity identified in the network of Fig. 8.5 is essentially associated with gathering, structuring or disseminating input or output information. Concurrently, each primary aspect to be considered in preliminary ship synthesis is mapped into relevant selection and compromise DSPs. As an aside, the general principles for developing or finding the 'best' network is a matter of current research. Some related work in progress is reported in (Bras and Mistree, 1991). Upon implementation on a computer we envisage that there could and should be similar models underlying all entries shown in the P-E-I diagram.

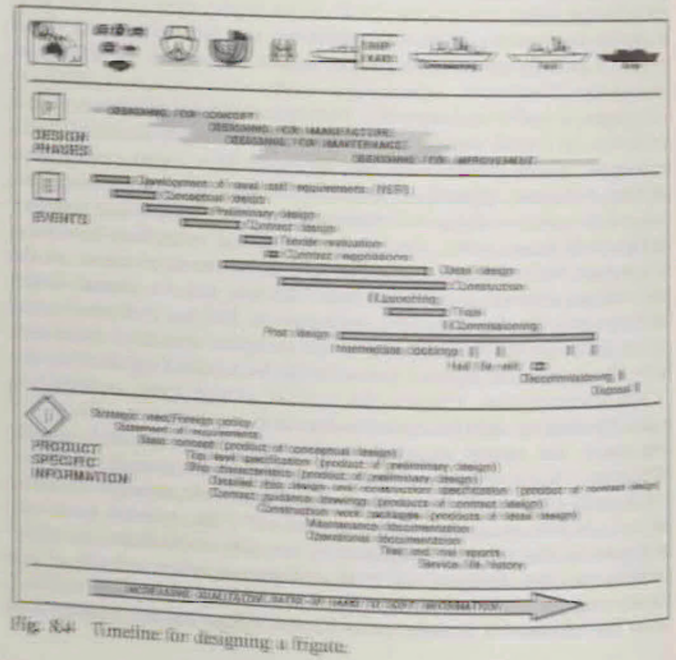


Fig. 8.4 Timeline for designing a frigate.

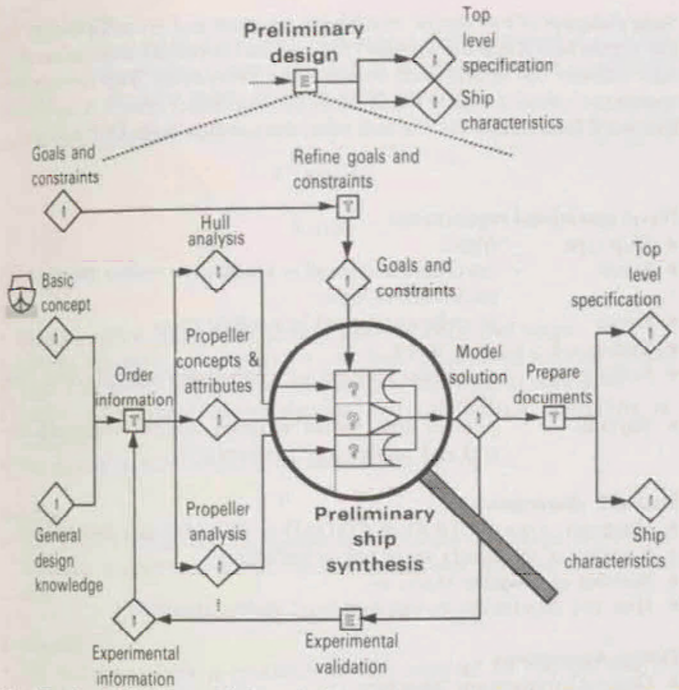


Fig. 8.5 A model of the preliminary design event.

8.4.2 Preliminary ship synthesis – concurrent design of the hull–propeller–machinery system

From a concurrent design perspective, what we seek is a holistic integrated model that yields a solution to all of the relevant decisions simultaneously. The model of the preliminary design event depicted in Fig. 8.5 demonstrates this. As shown, it remains open ended as the individual decisions to be addressed in the preliminary ship synthesis could be many. Restricting our discussion to the gross design elements, in traditional preliminary design the hull is designed first. The propeller is then designed and minor sequential and iterative modifications are made to integrate the hull and the propeller. Finally, the machinery is selected to match the system as well as it can. In Fig. 8.5 we illustrate a coupled DSP for preliminary ship synthesis that involves these elements of hull design, machinery selection and propeller design. The key notion here is that the coupled DSP enables concurrent solution by taking into account the interactions between the subsystems. The solution represents the holistic design of a hull–propeller–machinery system. A representative word formulation for the hull subsystem compromise DSP follows.

Given

Naval operational requirements

- Ship type – frigate
- Speed – maximum sustained in knots
  – endurance in knots
- Range – at endurance speed in nautical miles
- Endurance – days at sea
- Seakeeping – maximum seastate for normal ship and helicopter operations
- Payload – number and type of weapons, aircraft, command, control and surveillance equipment

Desirable characteristics

- Machinery type (CODOG or CODAD or COGAG or steam turbine)
- Location of machinery space (aft or midships)
- Number of propeller shafts
- Hull and superstructure material (steel and/or aluminum)

Design Assumptions

- General arrangement 'geometry'

and a starting design:

$$\mathbf{X}^0 = \{X_i^0 : i = 1, \ldots, M\}$$

Find

The values of system variables

$\mathbf{X}^* = \{X_i^* : i = 1, \ldots, M\}$ as defined by the principal ship dimensions:

L	length between perpendiculars in meters
B	ship design beam in meters
T	ship design draft in meters
D	ship design depth in meters

The form coefficients:

C_b	block coefficient
C_p	prismatic coefficient
C_w	waterplane coefficient
C_m	midship section coefficient

and parameters:

LCB	longitudinal center of buoyancy in meters forward of midships
LCF	longitudinal center of flotation in meters forward of midships
SDKHT	standard height between decks in meters

and the deviation variables:

$$d^+ \text{ and } d^-$$

Satisfy

The following system constraints:

Space

- Displacement is equal to or greater than the estimated weight
- Internal volume is equal to or greater than the required internal volume
- Total deck area is equal to or greater than the required deck area
- Length must exceed aerial, weapon and ship system separation requirements
- The double bottom height is between 0 and 1.5 meters

Stability

- The intact stability in the minimum operating condition exceeds the minimum requirement determined in accordance with the stability criteria.

Seakeeping

- The seakeeping rank is greater than that required for the specified sea state for normal ship operations and for helicopter operations
- The natural period of roll is greater than the period of encounter
- The natural period of heave is greater than 120% of the period of encounter relevant to heave, i.e., ship operates in supercritical region
- The natural period of pitch is greater than 120% of the period of encounter relevant to pitch, i.e., ship operates in supercritical region
- Freeboard is greater than the required freeboard at midships

Form

- The prismatic coefficient is within limits defined by the speed–length ratio
- The LCF is at least a given percentage aft of the LCB
- The form coefficient relationship, $C_b = C_p^* C_m$
- Minimum and maximum values for:

  L/B, L/D, L/T, B/D, B/T, T/D, C_b/C_w, C_b/C_p and C_w/C_p

The following system bounds ($\mathbf{X}^{\min} \leq \mathbf{X} \leq \mathbf{X}^{\max}$):

- All variables, except LCB and LCF, must be positive

The following system goals:

- The capital cost is equal to or smaller than the target value

- The seakeeping quality is equal to or greater than the target value
- The endurance speed powering is equal to or smaller than the target value
- The maximum sustained speed powering is equal to or smaller than the target value
- The displacement is equal to or smaller than the target value
- The height between decks is equal to or greater than the target value

Minimize

The deviation function

$$Z=\{f_1(d^-,d^+),\ldots,f_k(d^-,d^+)\}$$

Intuitively, a library of such DSP templates can be created and used widely on relevant problems. For example, an appropriate template for propeller design could be used in conjunction with a multitude of hull form templates.

And now to model the subsystems as a coupled DSP as depicted mathematically in Table 8.2. Generally, a ship's subsystems (e.g., hull design, propeller design and machinery selection), are highly dependent in respect to the total ship system. For example, the attribute ratings for the machinery selection are influenced by the geometric system variables of the ship's length, beam, depth, etc. Similarly, the values of the hull goals are dependent upon the machinery selected and the performance of the propeller. Essentially, this interaction is modeled by coupling the decision subsystems and/or establishing a decision hierarchy. This form of interdependency and hierarchy of decisions is typical of real-world design problems and has been addressed in (Smith *et al.*, 1987). The mathematical justification for this coupling is presented in (Karandikar *et al.*, 1991).

With little imagination, it is easy to see the interplay between subsystems considering the goals of each. The goals for the hull subsystem are identified above as:

- Achieve the desired capital cost;
- Achieve the desired seakeeping quality;
- Achieve the desired endurance speed powering;
- Achieve the desired maximum sustained speed powering;
- Achieve the desired displacement; and
- Achieve the desired height between decks.

Similarly, for the propeller subsystem the goals may be:

- Achieve the desired efficiency; and
- Achieve the desired matching of the propeller and ship thrust coefficients.

Finally, the propulsion machinery subsystem goals could be:

- Achieve the desired capital cost;
- Achieve the desired machinery weight;

- Achieve the desired volume of machinery spaces;
- Achieve the desired range; and
- Achieve the desired reliability.

The same goal (and constraints) may occur in multiple subsystems and the assignment of specific goals to specific subsystems is a question open to debate. However, when subsystems are integrated, the goals are concatenated together in a single set and duplicates are discarded. This leads to a composite deviation function.

Moving to mathematics, the succinct statement of the coupled hull/propeller/machinery system math formulation would be similar to that provided in Table 8.2. The bounds on the system variables (e.g., $100\,m \leqslant X_1 \leqslant 200\,m$: $X_1 = \mathrm{L}$) and the linear constraints representing hull geometry 'design lanes' (e.g., $1.220 \leqslant 1.0942{*}X_5 + 1.0{*}X_7 \leqslant 1.260$: $X_5 = C_b$ and $X_7 = C_w$) are easily represented algebraically. However, the nonlinear constraints and goals cannot be so easily represented. Each is typically encoded in a subroutine or set of subroutines.

In the foregoing, we have addressed an example of meta-design, detailed in words a decision template and discussed the modeling of subsystems that result in concurrent design. Let us now turn our attention to some numerical examples.

8.4.3 A container ship example

The problem statement for this example is as follows. Assume that a market exists for transporting containers between two ports 6,000 nautical miles apart. A forecast of the operating costs and market revenues has been made and a 15% minimum rate of return on investment (ROI) is desired. A 60% average load factor is assumed for the vessel since the market is seasonal and a larger cargo capacity will be necessary at certain times of the year. Due to economic considerations, the owner has specified a ship that has a cargo capacity of 650 TEUs (twenty foot equivalent units), where the average weight of a unit is assumed to be 20 tons. Determine an initial estimate of the principal dimensions and associated ship characteristics for a container ship in such service. Assume that the technical goals stated for the design are:

- Achieve the desired deadweight to displacement ratio;
- Achieve the target cargo capacity of 650 TEUs;
- Achieve the target GM of 2.0 meters;
- Achieve only the classification freeboard;
- Achieve the desired resistance; and
- Achieve the target speed.

The economic goals for the design are:

- Achieve at least the target ROI of 15%; and
- Achieve the desired vessel cost.

A DSP template was created for this decision such that an estimate of through-life economic characteristics could be made, and that the hull lowering information could be calculated with or without consideration of the propeller design (by using different algorithms). The highest priority was placed on achieving at least the target ROI and the target speed. The second level sought to achieve the required cargo capacity of 650 TEUs. Some characteristic data from a parametric study using this DSP is tabulated in Table 8.3. Cases were run for various target speeds over a range from 10 to 24 knots assuming one of the following:

- Concurrent design of hull and propeller with economic considerations ('H/P/E'); or
- Design of hull only with economic considerations ('H/E'); or
- Design of hull only without economic considerations ('H only').

The units of the data presented in Table 8.3 are as follows:
- L, B, T, D – meters;
- C_b – block coefficient (dimensionless);
- SHP – metric horsepower in thousands;
- VK – vessel speed knots;
- ROI – return on investment as a percentage; and
- CAP – cargo capacity in TEUs.

The subsequent plots of this data are, in the main, given against speed-length ratio (V/LO^5), with speed in knots and length in feet. The examples cover a range of speed-length ratio from 0.72 to 0.92 that corresponds to Froude numbers between 0.21 and 0.28.

As a function of the container ship DSP template used, the powering algorithm invoked for 'H/E' and 'H only' scenarios is based on the Series 60 work of Shaher Sabit (1972). In contrast, 'H/P/E' calls on a composite algorithm that utilizes the power prediction method proposed by Holtrop and Mennen (Holtrop and Mennen, 1982; Holtrop, 1984), coupled with the Wageningen B-screw series data presented by Oosterveld and van Oossanen (1975). The economic model, when invoked, for 'H/E' and 'H/P/E,' is identical. All other analytical calculations are identical across scenarios.

We include the containership example not to illustrate the design of a perfect ship but rather to demonstrate the process of designing under the DSPT umbrella. Therefore, we suggest that the data be looked at qualitatively rather than quantitatively. Now, given the template and the set of parametric data, what are some of the characteristic observations that can be made about the model and the decision support provided by using the model?

Various hull form design lanes were specified as constraints in this model (e.g., $(L/B)^{min} \leq L/B \leq (L/B)^{max}$). However, philosophically, a design with specifications outside these design 'trend' ranges is not necessarily infeasible or unacceptable. These constraints only represent statistical data compiled for 'similar' ships and remaining within such accepted and proven ranges

Table 8.3 Parametric data for container ship

	Ship speed (knots)									
	10	*12*	*14*	*15*	*16*	*17*	*18*	*20*	*22*	*24*
Hull and propeller with economic considerations ('H/P/E')										
L	123.3	117.3	123.8	123.1	122.0	123.7	124.8	125.1	124.7	123.8
B	22.02	20.94	22.10	21.97	21.79	22.09	22.28	22.34	22.17	22.11
T	9.390	10.47	9.360	9.400	10.78	11.04	11.14	11.17	10.89	10.94
D	11.23	14.24	11.22	11.24	12.51	12.81	12.93	12.96	12.68	12.72
CB	0.737	0.729	0.734	0.742	0.673	0.647	0.630	0.625	0.650	0.651
SHP	7.720	6.520	6.970	7.620	9.040	10.57	13.91	12.28	11.92	12.54
VK	14.80	14.43	14.87	15.00	16.00	17.00	18.00	17.84	17.50	17.55
ROI	17.30	18.00	18.30	18.50	25.00	26.50	22.50	25.00	25.00	24.00
CAP	646.0	632.0	650.0	648.0	663.0	658.0	624.0	640.0	644.0	638.0
Hull only with economic considerations ('H/E')										
L	123.4	134.7	116.8	125.7	122.3	124.3	124.9	126.4	125.6	125.6
B	22.04	24.37	20.83	22.44	21.84	22.20	22.31	22.53	22.43	22.43
T	9.380	9.380	10.41	9.310	10.50	10.71	11.15	11.26	11.21	11.21
D	11.18	10.71	13.77	11.16	12.26	12.49	12.92	13.09	13.02	13.02
CB	0.735	0.704	0.730	0.707	0.657	0.631	0.692	0.610	0.618	0.618
SHP	8.130	3.160	3.330	6.630	6.880	8.340	10.44	11.50	11.66	11.66
VK	15.00	14.57	14.33	15.33	16.01	17.00	18.04	18.55	18.55	18.55
ROI	20.30	18.00	21.00	20.30	25.50	26.50	26.50	29.50	29.50	29.50
CAP	649.0	648.0	648.0	642.0	646.0	639.0	649.0	649.0	650.0	650.0
Hull only without economic considerations ('H only')										
L				126.8	123.8	127.0	127.4			
B				22.31	22.04	22.21	22.62			
T				9.380	10.43	10.83	11.30			
D				11.30	12.29	12.69	13.15			
CB				0.698	0.648	0.619	0.593			
SHP				5.810	6.880	8.340	10.09			
VK				15.10	16.06	17.01	17.99			

only assures the designer that the generated design will not be extraordinary. Indeed, the experience and knowledge gained from past designs is important for directing the creation of a new design, but a new design should not be limited by past trends. A close analysis of the solutions generated must be made so as not to limit the design to the ordinary when the extraordinary is called for and is possible. For instance, if a particular design trend constraint is active in the final design for several, slightly varied models, then a close examination of the reasons for this limiting activity should be made. If appropriate the limiting constraint should be relaxed to allow the design to move to another, perhaps more meaningful, limiting constraint.

A design trend constraint that was consistently active in the parametric study was $(L/B)^{min}$; it was set at 5.6. The L/B ratio plotted against speed-length ratio for each case is shown in Fig. 8.6. It is observed that nearly all of the designs generated which include economic goal constraints ('H/E' and 'H/P/E') are limited by $(L/B)^{min}$. One might correctly reason that the economic considerations are driving the design to a minimum length. However, further investigation is probably warranted in order to establish the true lower bound on (L/B). It is suggested under such circumstances that the active design trend constraint be treated like a secondary goal. From a designer's perspective, trends should not be adhered to as strictly as system constraints, but they should be allowed to focus the problem. As a final comment here, the use of trend data is extremely useful and is not unique to naval architecture. The same type of experience-based design is used in almost all major engineering systems.

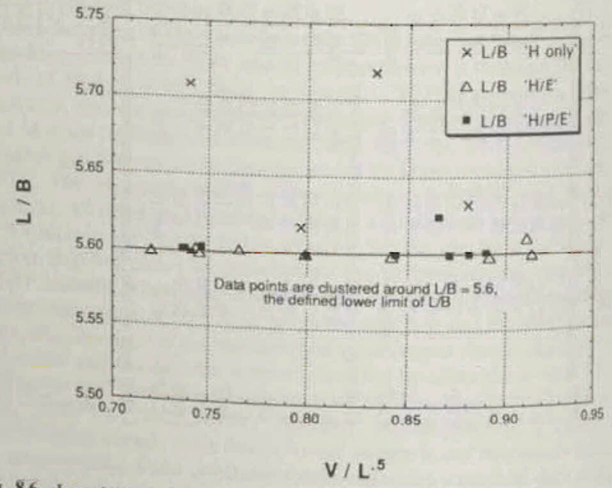


Fig. 8.6 Length/beam v. speed length ratio.

Remembering that the parametric study covered a target speed range of 10 to 24 knots, it is noted that results for 'H only' are only provided for target speeds of 15 through 18 knots. At either end of the spectrum, satisfactory convergence could not be achieved based on technical efficiency alone. While results for the runs involving the explicit economic goal produced results for cases with target speeds outside this range, the achieved speeds were still effectively held to this range. This phenomenon is depicted clearly in Fig. 8.7. In effect, at low speeds, the economics of the scenario said, 'it's all right to increase speed'. Similarly, at the other end of the spectrum, the best tradeoff between economic and technical efficiencies limited speed to about 18 knots.

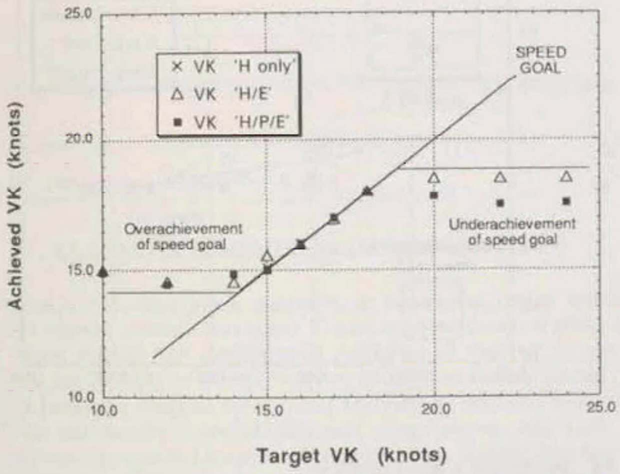


Fig. 8.7 Achieved speed v. target speed.

Some other observations are that at low speed ratios, the final designs as plotted seem to indicate two possible solutions, at least with respect to dimensional ratios. By exploring the convergence history for each solution (though not done here), we could perhaps gain some further insight. This would be particularly so if we were to identify converging subsequences generated by the optimization algorithm. Given that these subsequences were identified, what does this imply to the designer? Simply, it identifies that the 'alternate' solutions are equivalent in terms of goodness as measured by the current deviation function; while at the same time being dimensionally and technically different. However, this dichotomy could be resolved by modifying the current set of goals better to reflect the designer's aspirations. In contrast, at the higher speed ratios, there appears to be convergence across all scenarios to a single solution. This is clearly demonstrated by the plot of B/D against speed-length ratio as shown in Fig. 8.8. At low speed ratios, a B/D of either 1.5 or 2.0 is identified while at higher speeds, a value of 1.75, plus or minus 'delta,' is strongly suggested. Further, at these higher speed ratios there is still an observable trend to decrease B/D as speed–length increases. This is in keeping with conventional wisdom where depth increases at a faster rate than beam or length. It is well-known that length is a very expensive parameter to increase. Indeed, many estimates of cost are based on length alone. Increases in length and/or beam generally increase resistance. The effect of increasing depth on the other hand tends to affect construction costs only.

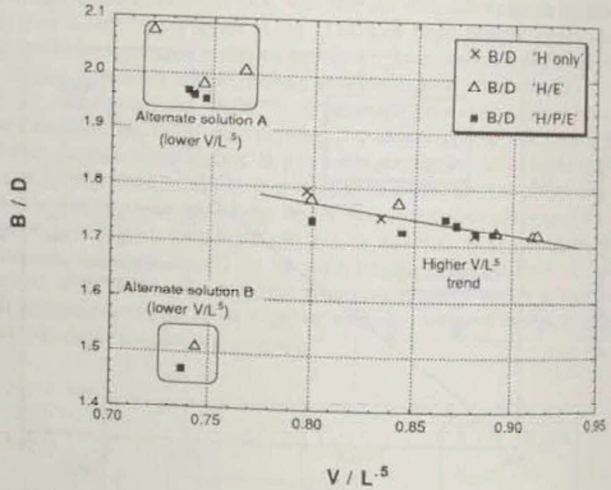


Fig. 8.8 Beam/depth v. speed–length ratio.

Finally, to lend further evidence to the claim that the model is reasonable for preliminary design studies, let us examine the trend in the displacement characteristics. Since the owner requires a fixed capacity of 650 TEUs, it is intuitively obvious that if this is achieved, displacement will increase with ship speed due to higher resistance, larger engines and greater fuel bunkering requirements. This trend is indeed evident in the model as shown in Fig. 8.9.

In summary, some anticipated trends have been highlighted lending weight to the validity of the template. Second, some insight regarding the interpretation of results has been provided, and third, some discussion regarding the use of the template to support the design process and its decision making has been entered into.

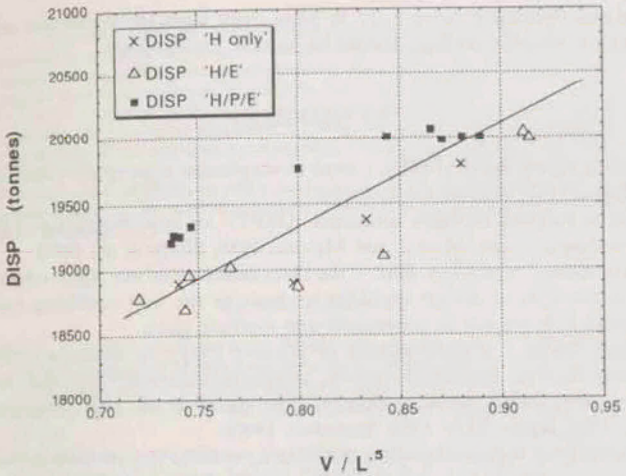


Fig. 8.9 Displacement v. speed–length ratio.

8.5 SOME COMMENTS ON IMPLEMENTATION

Presented is a decision-based approach to concurrent design called the decision support problem technique. Concurrency of design is achieved in one respect through the simultaneous resolution of 'derived' or multiple decisions (see Fig. 8.1). In another respect, all decision models, primary and derived, inherently integrate the required analysis and synthesis components of design and thereby support concurrent design activity (see Table 8.2). General experience with this approach across a range of disciplines has been very encouraging. This is evidenced by the example highlighted herein and those case studies cited through the reference list.

The development and validation of significant decision models is a non-trivial task and as with any modeling process, the law of 'garbage in – garbage out' applies. For meaningful results, a commitment to the development of the appropriate tool-box for a domain specific field of application is mandatory. This is particularly true during the initial DSPT implementation phase within an organization while the domain specific analysis tool library is developed into a modular and DSPT usable form. Further, education programs that encourage people to learn how to cope with and to be agents of change need to be developed. Designers need to learn how to make adjustments in their personal and/or organization's design paradigms and best practices. We are all creatures of habit. But, we must be prepared to adopt and merge new ideas in order to survive. We believe that once the tools and thought processes are in place, fruit from the concurrent act of designing complex artifacts should be quickly forthcoming.

8.6 GLOSSARY

Decision-based design (DBD): a term to emphasize a perspective for design (Shupe, 1988; Mistree *et al.*, 1989).

Decision support problem technique (DSPT): an implementation of decision-based design (Muster and Mistree, 1988; Shupe *et al.*, 1988).

Compromise – a primary DSP – the determination of the 'right' values (or combination) of design variables to describe the best satisficing system design with respect to constraints and multiple goals.

Derived DSPs – a combination of primary DSPs to model a complex decision, e.g., selection/selection, compromise/compromise and selection/compromise decisions (Smith, 1985; Smith *et al.*, 1987; Bascaran *et al.*, 1989; Karandikar, 1989; Bascaran, 1990).

Meta-design: a metalevel process of designing systems that includes partitioning the system for function, partitioning the design process into a set of decisions and planning the sequence in which these decisions will be made.

Designing: a process of converting information that characterizes the needs and requirements for a product into knowledge about a product.

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8.8 NOTES

1. We consider efficiency to be a measure of the swiftness with which information required by a designer is generated.
2. We consider effectiveness to be a measure of the quality of a decision (correctness, completeness, comprehensiveness) made by a designer.

3. {……} indicates a set.
4. (…,…) indicates arguments for the operator preceding the left parenthesis. The arguments separated by a ',' must be present for the operator to be valid.
5. Procedural knowledge is the knowledge about the process, i.e., knowledge about how to represent (and process) domain information (for design synthesis).
6. Declarative knowledge is the set of facts represented (usually) according to the protocol defined by the procedural knowledge. It is the knowledge about the product, i.e., the representation of problem relevant information, facts and background knowledge about the domain.
7. Decision support problems provide a means for modeling decisions encountered in design and the domain specific mathematical models so built and implemented on a computer are called templates.

8.9 REFERENCES

Bascaran, E. (1990) *A Conceptual Model for the Design of Thermal Systems: concurrent decisions in designing for concept*, Department of Mechanical Engineering, University of Houston, Houston, Texas.

Bascaran, E., Bannerot, R. B. and Mistree, F. (1989) *Engineering Optimization*, **14**, 207–38.

Bras, B., Smith, W.F. and Mistree, F. (1990) in *CFD and CAD in Ship Design*, (ed G. v. Oortmerssen) Elsevier Science Publishers B.V., Wageningen, The Netherlands, 221–31.

Bras, B.A. and Mistree, F. (1991) Designing design processes in decision-based concurrent engineering, *Proceedings SAE Aerotech '91*, SAE Publication SP-886, Paper No. 912209, Long Beach, California, SAE International, 15–36.

Holtrop, J. (1984) *International Shipbuilding Progress*, **31(363)**.

Holtrop, J. and Mennen, G. G. J. (1982) *International Shipbuilding Progress*, **29(385)**.

Ignizio, J.P. (1982) *Linear Programming in Single and Multi-Objective Systems*, Prentice-Hall, Englewood Cliffs, New Jersey.

Ignizio, J.P. (1983) *Computers and Operations Research*, **5(3)**, 179–97.

Ignizio, J.P. (1985) *Introduction to Linear Goal Programming*, Sage University Papers, Beverly Hills, California.

Ignizio, J.P. (1985) *European Journal of Operational Research*, **22**, 338–46.

Kamal, S.Z. (1990) *The Development of Heuristic Decision Support Problems for Adaptive Design*, Department of Mechanical Engineering, University of Houston, Houston, Texas.

Kamal, S.Z., Karandikar, H. M., Mistree, F. and Muster, D. (1987) in *Expert Systems in Computer-Aided Design*, (ed. J. Gero) Elsevier Science Publishers B.V., Amsterdam, 289–321.

Karandikar, H.M. (1989) *Hierarchical Decision Making for the Integration of Information from Design and Manufacturing Processes in Concurrent Engineering*, Department of Mechanical Engineering, University of Houston, Houston, Texas.

Karandikar, H.M. and Mistree, F. (1992) in *Structural Optimization: Status and Promise*, (ed. M.P. Kamat) AIAA, Washington, D.C.

Karandikar, H.M., Rao, J.R. and Mistree, F. (1991) in *Advances in Design Automation*, (ed. G.A. Gabrielle) ASME, New York, 361–9.

Klir, G.J. (1985) *Architecture of Systems Problem Solving*, Plenum Press, New York.

Kuppuraju, N., Ittimakin, P. and Mistree, F. (1985) *Design Studies*, **6(2)**, 91–106.

Lyton, T.D. and Mistree, F. (1984) *Journal of Ship Research*, **29(4)**, 251–69.

Mistree, F., Hughes, O.F. and Bras, B.A. (1992) in *Structural Optimization: Status and Promise*, (ed. M.P. Kamat) AIAA, Washington, D.C.

Mistree, F., Hughes, O.F. and Phuoc, H.B. (1981) *Engineering Optimization*, **5(3)**, 141–4.

Mistree, F., Muster, D., Shupe, J.A. and Allen, J.K. (1989) *A Decision-Based Perspective for the Design of Methods for Systems Design*, Recent Experiences in Multidisciplinary Analysis and Optimization, Hampton, Virginia, NASA.

Mistree, F., Muster, D., Srinivasan, S. and Mudali, S. (1990) *Mechanism and Machine Theory*, **25(3)**, 273–86.

Mistree, F., Smith, W.F., Bras, B., Allen, J.K. and Muster, D. (1990) in *Transactions, Society of Naval Architects and Marine Engineers*, Jersey City, New Jersey, 565–97.

Muster, D. and Mistree, F. (1988) *The International Journal of Applied Engineering Education*, **4(1)**, 23–33.

Oosterveld, M.W.C. and Oossanen, P. v. (1975) *International Shipbuilding Progress*, **22(251)**, 251–62.

Rich, E. (1983) *Artificial Intelligence*, McGraw Hill.

Shaher Sabit, A. (1972) *International Shipbuilding Progress*, **19**.

Shupe, J.A. (1988) *Decision-Based Design: taxonomy and implementation*. Department of Mechanical Engineering, University of Houston, Houston, Texas.

Shupe, J.A., Muster, D., Allen, J.K. and Mistree, F. (1988) in *Expert Systems, Strategies and Solutions in Manufacturing Design and Planning*, (ed. A. Kusiak) Society of Maufacturing Engineers, Dearborn, Michigan, Chapter 1, 3–37.

Smith, W.F. (1985) *The Development of AUSEVAL: An automated ship evaluation system*. Department of Mechanical Engineering, University of Houston, Houston, Texas.

Smith, W.F., Kamal, S.Z. and Mistree, F. (1987) *Marine Technology*, **24(2)**, 131–42.

CHAPTER 9

Concurrent optimization of product design and manufacture

Masataka Yoshimura

9.1 INTRODUCTION

Recently, the circumstances in product design and manufacturing of machine products have greatly changed. The times in which computer-aided systems such as computer-aided design (CAD), computer-aided manufacturing (CAM), computer-aided engineering (CAE) and computer-aided process planning (CAPP) were independently developed are changing to one in which these fields are integrated and product design and manufacturing are rationally and efficiently conducted using computer systems. So, CIM (computer-integrated manufacturing), concurrent engineering (Brazier and Leonard, 1990; Haug, 1990) and simultaneous engineering (Foreman, 1989) have attracted special interest recently. The major goals of these technologies are to realize higher product performance, lower manufacturing cost, shorter lead time and automation of a variety of low-volume production systems, etc. (Hitomi, 1979).

This chapter describes fundamental methodologies for concurrently optimizing decision making items concerning product design and manufacturing. Concurrent optimization is a key for realizing a product having higher product performance and lower product manufacturing cost from a global viewpoint.

9.2 FLOW AND RELATION OF RESEARCH AND DEVELOPMENT, PRODUCT DESIGN, MANUFACTURING AND MARKETING DIVISIONS

Figure 9.1 shows a conventional product manufacturing flow of research and development, product design, manufacturing and marketing and the