AN AXIOMATIC APPROACH TO PERFORMANCE-BASED DESIGN

by

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B.S. Civil Engineering, Tufts University (1982)
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Submitted to the Department of Civil Engineering in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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ABSTRACT

Citing product quality as a mechanism for advancing the competitive advantage of the U.S. construction industry, this thesis outlines and demonstrates a methodology for performance-based design of constructed facilities. The concept of performance-based design is offered as a strategy for facility development: a rational basis for satisfying owners' requirements in various areas of project performance, such as service, durability, ease of construction, and ease of maintenance. The proposed methodology is a systems-based approach to design where the principles of Axiomatic Design as advanced by Dr. Nam P. Suh provide a mathematical framework for making the implications of various design alternatives explicit and for reasoning about the merit of design decisions.

Specifically, the Independence Axiom is used to ensure the advancement of solution concepts that are controllable, and the Information Axiom is used to quantify "how well" a proposed design satisfies the governing requirements. The Information Axiom has been extended to include the notion of an Interface Index as a quantitative design aid for reasoning about the complexity associated with system integration. The proposed Interface Index is an information-based metric derived from graph theory, and it is similar to the family of complexity metrics that have been developed for evaluating the modularity of software systems. The validity of the proposed design methodology, including the Interface Index, is demonstrated through application to a case study.

Thesis Supervisor: Dr. Jerome J. Connor
Title: Professor of Civil Engineering
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With love to

Kathy, Christopher, and Julianne
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GLOSSARY OF TERMS

Axioms. By definition, axioms are fundamental truths that are always observed to be valid and for which there are no counterexamples or exceptions. Axioms may be hypothesized from a large number of observations by noting the common phenomena shared by all cases; they cannot be proven or derived, but they can be invalidated by counterexamples or exceptions.

Constraint. A certain requirement which represents the bound on an acceptable design solution. By definition, a constraint is different from an FR in that a constraint does not have to be independent of other constraints and FRs. Constraints do not normally have tolerances associated with them, whereas FRs typically have tolerances.

Design axioms. The axioms which govern good design. There are two design axioms. The Independence Axiom provides the criterion for acceptable design during the mapping process and the Information Axiom selects the best among acceptable solutions.

Design domain. Design domains separate "What we want to achieve" from "How are we going to achieve what we want". Furthermore, within each domain there is a characteristic vector which can be decomposed into a hierarchy. In the construction industry, there are at least four design domains: client domain, functional domain, physical domain, and process domain. The client domain is "what", whereas the functional domain is "how" relative to the client domain. In turn, the functional domain is "what" relative to the physical domain, which is "how". Lastly,
the physical domain is "what" relative to the process domain, which is "how".

**Design range.** The tolerance which is associated with the FR or DV specified by the designer.

**Design variables (DV$s$).** The key variables in the physical domain which characterize the physical entity created by the design process to fulfill the FR$s$.

**Functional coupling.** A design is functionally coupled when some of the functions are dependent on other functions, and thus violates the Independence Axiom.

**Functional requirements (FR$s$).** A minimum set of independent requirements that completely characterize the functional needs of the product design in the functional domain.

**Interface.** Communication link between engineering disciplines or construction tradesmen arising from functional dependencies.

**Mapping.** The synthesis phase of the design process which accompanies the interplay between any two design domains representing "What we want" and "How we will satisfy what we want" respectively.

**Performance requirements (PR$s$).** Set of attributes that characterize the desired needs of the project in the client domain.

**Process variables (PV$s$).** The key variables which characterize the construction process to fulfill the selected set of DV$s$. The relationship between DV$s$ and PV$s$
is such that DVs represent the requirements that the PVs must satisfy in the process domain.

**System range.** The capability of the physical system or processing system given in terms of tolerances.
Chapter 1 Introduction

1.1 Introduction

As civil engineering enters the 21st century, the demands on the profession will move toward complex, interdisciplinary tasks such as infrastructure rehabilitation, environmental cleanup, and the delivery of high-technology facilities, such as hospitals, R&D laboratories, and advanced manufacturing plants, [1]. The success of the U.S. construction industry in these future markets requires a competitive strategy for securing a share of the global market. Following the lead of the manufacturing industry, a key aspect of this strategy is the ability to produce quality projects.

Quality is a fashionable, catch-all term for describing how well a particular constructed facility meets owner/user needs in one or more performance areas, such as functionality or serviceability, speed of construction, and life-cycle economy. Lemer [26] foresees a shift in industry focus from "physical facilities to the shelter and services that these facilities are meant to provide for a period of years." This shift implies responsiveness to long-term owner/user needs rather than the short-term needs of speculative developers and interim owners. Therefore, it is anticipated that life-cycle performance issues will be integrated into the project development process, and competitive bidding for development contracts will include life-cycle costs, [26]. The National Materials Advisory Board [30], for example, has recommended extending the current concept of construction bonds to include performance bonds as a surety for satisfactory durability of concrete structures.
New technologies, such as advanced building materials and automated construction systems, are areas of research and development that can make important contributions toward improving project quality and securing competitive advantage, [40]. Advanced technological resources by themselves, however, are insufficient because the quality of any project is ultimately tied to the effectiveness of the human resources working in the areas of design, construction planning, and construction operations. This inescapable dependence on human resources brings the methods by which the various participants interact and perform their tasks to a position of preeminence.

1.2 Problem Statement

The project delivery process can be generalized to include the following seven stages: programming, conceptual planning, preliminary design, detailed design, construction planning, procurement, and construction operations. Traditionally, each stage has been delineated by distinct interfaces reflecting changes in the types of information being processed, changes in responsible personnel due to technical proficiency, the practice of split contracts for design and construction services, and the increasing role of specialized subcontractors. Although alternative project delivery strategies, such as design/build, turnkey, and modular, fast-track construction [12,34], are merging construction planning, procurement, and construction operations within the conceptual planning, preliminary design, and detailed design stages, communication barriers still exist between design and construction personnel, as well as between design disciplines.
The responsible architect or design manager, after discussions with the owner/user, uses experience gained from similar facilities to establish a concept solution and to identify the critical, supporting subsystems, [20]. The subsequent design of these subsystems is then distributed among subordinate parties, such as structural, mechanical, and electrical engineers. The actual selection of the responsible engineering firms can occur through competitive bidding or a pre-arranged consortium.

Within each engineering discipline, the subsystem descriptions progress from conceptual plans to preliminary designs to detailed designs in a top-down or hierarchical manner. There is an incremental refinement of the engineering output as the level of detail evolves from abstract concepts to drawings and specifications supporting the finalization of the design package and the generation of construction documents. At each level of abstraction, design knowledge is applied in the following sequence, [14,18,20,37]:

1. Problem identification.
2. Synthesis.
3. Evaluation.

Problem identification involves studying the problem at hand and formulating a set of governing objectives or requirements for its solution. Synthesis refers to the creative process of generating potential solutions. These solutions are then evaluated with respect to the governing criteria. The result of these evaluations is a subset of one or more solution alternatives that are judged suitable for advancement. The output of the detailed design stage, for example, is a set of drawings and specifications that fully define the constructed system to those individuals
involved in the subsequent procurement and construction activities.

Consider the design of structural subsystems for buildings. Conceptual planning is performed by a senior structural engineer who is guided by past experience with precedent designs. Relying on the ad hoc, as well as creative use of analogy, imitation, or extrapolation, he generates a set of solution alternatives for the vertical and lateral load-resisting subsystems. Since substantive evaluations are difficult to perform at the concept level, the process of winnowing this solution set into a unique structural configuration requires iterations between the conceptual planning and preliminary design stages. During the preliminary design stage, a combination of rules-of-thumb and approximate first-order calculations are used to establish key dimensions, member spacings, and cost estimates for each solution alternative. This data must be compared with the constraints imposed by the functional layout, aesthetic concerns, construction resources, and project financing so as to determine suitability.

Once an acceptable structural solution is identified, it is passed to the detailed design phase. The objective of detailed design is to generate comprehensive descriptions of the structural elements and connections. The detailing process requires the decomposition of the structural subsystems on the basis of their load paths and the application of fundamental concepts of mechanics in order to dimension components and modify subsystem performance. The objective of detailed design is to ensure that regulatory code requirements [2,3,4,9] governing structural safety and serviceability are satisfied.
The explosive growth of computational methods over the past three decades has contributed to a situation in which much of the design effort beyond conceptual planning is performed automatically, involving a progression of computer programs and quantitative evaluations that typically culminate with least-cost optimization schemes. In fact, structural optimization is often offered as a methodology for enumerating the various design parameters associated with the topology and dimensions of members, as well as the selection of construction materials, [23]. Reference 25, for example, is organized so that any structural engineer seeking to optimize his design with respect to weight, strength, or stiffness can readily find an appropriate method from a bibliography of published work.

Thus, the current project delivery process for constructed systems is characterized by both a fragmented approach to design and construction planning and a non-homogeneous approach to decision-making within the various fragments. Unfortunately, these characteristics limit the industry's ability to respond to the challenge of designing and building higher quality facilities. Specifically, weaknesses arise in the areas of subsystem design and subsystem integration that hinder the delivery of complex, innovative facilities.

Firstly, design experts involved in conceptual planning tend to internalize their thought processes. Concepts are selected on the basis of heuristics without an explicit expression of objectives. Conceptual planning is viewed as an art, a skill "acquired as the result of knowledge and practice" [17], and as an art form, concept solutions are considered difficult to evaluate rationally in terms of function and efficiency, [17]. However, much of the
The difficulty associated with understanding design decisions is due to the fact that the underlying knowledge is not yet codified, organized, or generalized for diffusion throughout the industry, [15].

Lack of formalization during conceptual design obscures the importance of early decisions on project evolution and reduces the effort to generate alternative solution proposals. Figure 1-1, extracted from Reference 13, demonstrates the importance of early design decisions. It shows that a significant portion of a project's cost is committed during the conceptual design stage, and there is decreasing contribution from the later, more formalized design stages. Steyert [35] refers to this condition as "the paradox of modern design": rigorous analytical methods and optimization schemes are used for decisions that impact project cost plus or minus seven percent, while decisions that impact project cost plus or minus thirty percent are derived from heuristics. Conversely, there is a drastically increased cost involved in making changes in the later, more formalized design stages. Thus, the complete set of performance requirements must be addressed at the start of the design process.

However, generating concept solutions that satisfy a comprehensive set of requirements may require the ability to synthesize new concepts in the absence of prior examples. As discussed in References 18, 19, 33, and 37, the reliance on ad hoc techniques, rather than rational design methods that address multiple objectives, is an obstacle to the advancement of new concepts because the knowledge bases are shallow and not generalizable in terms of more fundamental knowledge. The lack of rational methods to select the best solution alternative can result
FIGURE 1-1. ABILITY TO INFLUENCE FINAL COST
(CONSTRUCTION INDUSTRY INSTITUTE, [13])
in the advancement of candidate solutions that are not wholly feasible for the problem at hand, forcing later design stages to compensate through inefficient, bottom-up approaches.

Secondly, the anticipated benefits of project fragmentation can be lost during subsequent integration of the various contributions into a total system. Fragmentation allows the design problem to be split up so that resources can be effectively allocated and applied to each sub-problem. Since certain sub-problems can be performed in parallel, the delivery process can also be significantly shortened, [20]. The difficulty in splitting the development of constructed systems is the fact that all of the fragments must eventually be integrated. As a result, the layout and connectivity of the various subsystems as well as the interfaces between construction tradesmen are as important as satisfying the functional requirements.

Traditionally, this integration and scheduling problem has been handled by a combination of past experience, industry standards, and construction management techniques. The introduction of additional performance requirements complicates the integration process by forcing designers and contractors to predict the side-effects associated with their decisions, particularly with regard to interfaces with other subsystems, [20]. Yet in References 18, 19, 31, 33, and 37, the point is made that the rise of computational methods has contributed to the development of an engineering community that can be characterized as a collection of highly technical, isolated knowledge domains requiring many years of experience to master. Due to this specialization, it is difficult for engineers to evaluate the performance of solution alternatives with respect to
multiple perspectives because each expert's knowledge base and computational tools are highly refined and do not address inter-disciplinary features of a problem. Isolated agents cannot determine the existence of incompatibilities between subsystems. Without a simple, yet explicit pattern for representing the integration issue, it is also difficult to determine whether the removal of major incompatibilities requires revising the overall project criteria or redesigning the affected subsystems, [20].

Weaknesses in the areas of subsystem design and subsystem integration can be demonstrated by considering the practice of structural engineering. For the structural engineer, the concept of design quality means that life-cycle issues such as ease of construction, durability, human comfort with respect to vibrations and motion perception, ease of maintenance, and demand on the environment are as important as the more traditional concerns of structural integrity, i.e. strength and stiffness. The process of selecting and detailing structural concepts so as to satisfy integrity has been well supported by a combination of strategies involving past experience, governing regulatory codes [2,3,4,9], and mathematical formulations (for example, matrix structural analysis). However, explicit methods to support design for construction, durability, or maintenance are lacking. If these additional requirements are addressed, it is usually in an ad hoc fashion only after major design decisions have been made, [31]. As a result, subsequent evaluation of design decisions made solely in response to considerations of structural efficiency may indicate that these decisions are inappropriate in the context of other functional requirements. For example, the design of a cast-in-place concrete structure for least weight does not
ensure a design that makes efficient use of construction resources, i.e. formwork and labor, [5].

1.3 Proposed Solution

To improve industry response to shifting objectives, this thesis proposes a methodology for performance-based design. The proposed framework is a systems-engineering approach [6,19,27,41] where the principles of Axiomatic Design as advanced by Suh et al. [29,36-39] describe an approach to the following activities:

1. Hierarchical decomposition of the design problem.
2. Successive mapping of functional requirements to design descriptions to construction operations.

Although the above activities do not describe a unique design methodology (for example, see References [16,18,19,20,33]), the merit of Axiomatic Design [36-39] is the existence of two design axioms that prescribe rational criteria for identifying a good design and for selecting the best solution from the set of alternatives. Thus, the design axioms provide an objective basis for externalizing the intent of the design process and for evaluating solution alternatives.

The first axiom is called the Independence Axiom [37]. As a principle for good design, it fosters the advancement of design solutions that explicitly satisfy the stated set of requirements and exhibit the system-theoretic properties of controllability and observability, [22,32]. Application of the Independence Axiom requires an explicit expression of functional requirements. Once these requirements are articulated, it provides a control strategy for the iterative process of generating and
evaluating solution alternatives. By representing the output of synthesis activities as a matrix transformation between the requirements and the set of design variables that characterize a particular solution alternative, the Independence Axiom brings all requirements to the fore and forces the designer to consider the side-effects associated with each solution alternative.

The second axiom is termed the Information Axiom [37]. It promotes the use of design solutions corresponding to best practice by advising the designer to chose those solution alternatives with the greatest probability of satisfying the functional requirements, i.e., minimum information content. The basic concept is that the greater the uncertainty associated with the success of a task, the greater the amount of information that has to be processed during task execution. This additional information corresponds to knowledge that must be learned during task execution so as to effect a satisfactory outcome. If a task has a high probability of success, then little information is needed during task execution beyond the activity's fundamental knowledge. Therefore, information content captures the technical complexity associated with the successful implementation of design and construction planning decisions.

The delivery of constructed systems that satisfy multiple needs requires the ability to reason about total facility performance. The appeal of the Information Axiom is the fact that it offers the concept of information content as a homogeneous method for evaluating relative design merit. For a given solution alternative, a constituent measure of information content can be determined with respect to each functional requirement. These constituent measures can then be summed to produce a total measure of suitability,
and this cumulative measure provides the designer with a quantitative means for relative comparison of competing design schemes.

This thesis expands the concept of quantifying relative design merit through information content to include the notion of an Interface Index. The Interface Index, as developed in Chapter 4, is offered as a quantitative design aid for reasoning about the complexities associated with subsystem integration. The proposed metric is an information-based measure derived from graph theory, and it is similar to the family of complexity metrics that have been developed for evaluating the modularity of software system designs as defined in [7,10,11,21,24,28,42,43]. It measures the amount of inter-system coupling associated with the integration of solution alternatives developed during the design and construction planning stages of the project delivery process. A rational measure of inter-system coupling aids in structuring solution alternatives so as to improve the ability of both designers and contractors to satisfy project requirements. In addition, the Interface Index as a measure of integration complexity can be combined with the aforementioned measure of technical complexity to create a total information-based measure for relative comparison of solution alternatives.

1.4 Research Objectives

The following research objectives have been identified as a means for substantiating the proposed methodology for performance-based design:

1. Develop and implement the methodology within a specific problem application.
2. Demonstrate the capacity to evaluate design decisions and to quantify performance at various levels of design detail.

3. Identify and verify targets for redesign in order to improve quality.

The first two objectives are an effort to verify the applicability of the design axioms [37] in the domain of constructed facilities. Past publications [29,36-39] have demonstrated the successful application of these axioms to the design of mechanical hardware, engineering materials, manufacturing processes, and organizations. Many of these applications can be classified as separable problems [16], such as flow systems or assemblies, in which each function is performed by a unique component and these components are only connected at specific inlets and outlets. The challenge of constructed facilities, on the other hand, is the perception that the design problem is difficult to split because constructed facilities are associative systems [16,20], i.e., each function is not satisfied by a distinct, isolated part, but the functions are spread over an integrated assembly. Thus, the applicability of the design axioms as a prescriptive criteria for achieving good design must be demonstrated through application to a case study involving an actual construction project.

In addition, the use of information content per the Information Axiom [37] as a relative measure for evaluating solution alternatives must be advanced. Past applications [29,36-39] have been somewhat limited in their use of the Information Axiom. To date, Nakazawa's contributions [29,37] in the area of manufacturing process planning are the most extensive treatment of the Information Axiom. The difficulty of applying the Information Axiom stems from the fact that it is dependent upon system range data which may not be readily available.

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Without a quantitative basis for comparing solution alternatives, however, many options must be advanced until sufficient criteria are available. Consequently, the impact of early design decisions becomes lost in design details. Therefore, the case study must also serve to demonstrate the feasibility of calculating design information content at various levels of abstraction.

Lastly, successful application of the design axioms, including the concept of the Interface Index, may identify one or more shortcomings in facility quality. These shortcomings can be recognized as violations of the Independence Axiom or decisions with relatively high information content. In either case, the validity of the design axioms as a prescriptive methodology for good design should be demonstrated by enabling redesign of the affected details.

The selected project is the parking garage for the Baybank Systems office complex in Waltham, MA. It is a cast-in-place, reinforced concrete structure with post-tensioned slabs. The garage project offers a reduced project scale for applying the concept of performance-based design. It provides a concise laboratory for reasoning about design and construction planning decisions and for studying the problems associated with integrating the contributions of various designers and subcontractors.

Since construction of the garage had just been completed at the start of my involvement, the process of implementing the proposed design methodology consists of working backward from the construction plans and design drawings to achieve convergence with project requirements. In this context, convergence means that the principles of Axiomatic Design are used to establish a consistent and
rational mapping from functional requirements to design specifications to construction plans. Once the mapping is established, the Information Axiom and proposed Interface Index are invoked in order to quantify project merit at each level of design detail. The design axioms and the Interface Index are then used to identify targets for redesign so as to improve design quality.

1.5 Organization of Thesis

This thesis consists of eight chapters. Following the current introductory chapter, six chapters (Chapters 2-7) comprise the body of the thesis, and there is one concluding chapter (Chapter 8). Brief summaries of the contents of Chapters 2 through 8 are given below.

Chapter 2 Framework for Performance-Based Design
This chapter presents the principles of Axiomatic Design [37] as a methodology for performance-based design of constructed facilities. The implications of the Independence and Information Axioms in the domain of constructed facilities are discussed. The chapter concludes with a design example demonstrating axiomatic design of a structural frame.

Chapter 3 Attributes of Performance
The adoption of performance-based design for the delivery of constructed facilities requires a shift in how design problems are identified. Various attributes of performance must be defined, as well as appropriate techniques for their measure. Therefore, this chapter outlines an operational framework that aids the designer in both prescribing functional requirements and measuring the capability of solution alternatives. The proposed
framework is based on the work of Billington [8] regarding critical analysis of architecture.

Chapter 4 Interface Complexity
For applications within a single domain, such as the design of mechanical assemblies, the Independence Axiom combined with the concept of information content has been shown [36-39] to be sufficient for evaluation and optimal selection of solution alternatives. The integration of the contributions from multiple disciplines, however, can introduce couplings that compromise functional independence. This chapter develops the concept of the Interface Index as a quantitative tool for reasoning about design optimality with regards to system integration.

Chapter 5 Application of Performance-Based Design to the Design of a Parking Garage: A Case Study
The concept of performance-based design is demonstrated and verified through implementation on an actual constructed facility: a parking garage for an office complex. Chapters 2 through 4 provide a basis for expressing the project's design and construction information in the context of the performance-based approach. The Information Axiom and Interface Index are then used to evaluate design merit.

Chapter 6 Targets for Design Innovation
The design axioms, including the Interface Index, are discussed as a prescriptive methodology for identifying targets for innovation. Innovative design is necessary when improved performance cannot be achieved with currently available techniques. The parking garage case study presented in Chapter 5 is reviewed to provide pertinent examples and alternative solutions are proposed.
Chapter 7 Strategy for Implementation

Much of the difficulty associated with the practice of performance-based design is related to efficient information processing. This chapter discusses organizational and computer-based strategies for improving information capabilities so as to advance performance-based design as a competitive alternative to the current project delivery process.

Chapter 8 Conclusions

The major points of the thesis are summarized, and conclusions are drawn concerning the concept of performance-based design. An outline of future research work is also presented.

1.6 Contributions

This thesis offers the following contributions to the problem of improving project quality during the design and construction of facilities and large-scale systems.

Firstly, a methodology for performance-based design has been developed and demonstrated. This methodology provides a rational framework for externalizing the design process and evaluating the capability of solution alternatives. A key aspect of this framework is the extension of the principles of Axiomatic Design into the domain of constructed facilities.

Secondly, the concept of the Interface Index establishes a quantitative basis for evaluating solution alternatives on the basis of the interfaces created by system integration. The Interface Index captures the complexity of design decisions due to inter-system coupling, as well as the complexity associated with the integration of construction
operations. The Interface Index in conjunction with the design axioms provides rational criteria for identifying targets for innovation and reasoning about proposed innovations.

Lastly, the work presented in this thesis can be used as an educational tool for the design of large-scale civil engineering systems. Systems engineering in civil engineering is not a well-recognized field of study or professional practice, [27]. However, the delivery of large, complex, multi-disciplinary projects requires the ability to integrate and evaluate fragmented solutions. The introduction of systems engineering to the civil engineering curriculum will provide a pool of engineers for industry to draw upon.
1.7 References


2. American Concrete Institute, Building Code Requirements for Reinforced Concrete, ACI Standard 318, Detroit: American Concrete Institute.


Chapter 2 Methodology for Performance-Based Design

2.1 Introduction

The development of a design methodology borrows from the concept of performance-based design as advanced over the past twenty years, initially by the European building community [1,2,3,9,14,15,16,19,22,27] and later adopted by the United States [30,31]. In practice, performance-based design has reflected an effort to apply systems engineering techniques [8,17,21,28,47] to the special problem of building design in the hope of advancing building technology through innovation. The performance of a building as a system is derived in a hierarchical manner from the performance of and the interaction among its supporting systems, sub-systems, and components.

The process of performance-based design as described in the literature starts with an expression of user needs. A functional analysis is used to translate these needs into explicit and quantitative statements of functional requirements, independent of any solutions and materials that may be applicable, [2]. The designer then synthesizes various candidate solutions based on a combination of creativity, engineering fundamentals, and practical forms of information pertaining to classes of building systems and products. The quantitative functional requirements then provide an objective basis for evaluating a particular solution and for comparing alternative solutions. Such an environment is suitable for innovation because the designer is free to explore radical concepts and non-traditional materials.

Much of the documented success with the performance concept
has occurred at the component level \([1,2,9,14,15,16,19,27]\). At this level of detail, the engineer is accustomed to dealing with quantitative requirements, such as component loadings, R-values for thermal insulation, and noise levels for sound insulation. Therefore, it was a natural progression for detailed performance requirements to form the basis for the specification and procurement of building products from vendors.

In response to this shift to performance criteria, the vendors have devoted a considerable amount of research effort to the testing, evaluation, and cataloging of new materials and products, \([16]\). Applicability of the performance concept throughout the entire design process has yet to be demonstrated on a widespread basis. This shortcoming stems from the lack of an accepted design methodology for transforming a project’s abstract performance requirements, which are often difficult to express in quantitative terms, into functional requirements and sub-requirements that define the building components and service systems, \([14,16,27]\).

"Operation Breakthrough" for innovative housing \([29,35,49,52]\) is one stark example of an ineffectual, large-scale application of the performance concept. The program was developed by the United States Department of Housing and Urban Development (HUD), and it sought to provide "housing for all income levels, through a partnership of labor, consumers, private enterprise, local, State and Federal Government, with the use of modern techniques of production, marketing, and management" \([49]\). The urgency of the initiative called in to question the feasibility of relying on conventional construction methods for a solution, and the need for revolutionary innovations in construction technology was cited, \([35]\). In order to foster innovation in the development of industrialized housing while avoiding
conflicts with restrictive building, housing, and zoning codes, HUD worked with the National Bureau of Standards to establish performance criteria [29] for the evaluation of structural safety and adequacy of building service systems. The partnership's inability to design, test, evaluate, and implement housing systems in a timely and cost-effective manner, however, led to significant cost overruns, bankrupt housing manufacturers, and, ultimately, the cancellation of the program, [38].

Although systems engineering [8,17,21,28,47] provides a logical framework for design, Axiomatic Design [42-45] contributes operational aspects that had been lacking in prior attempts to advance performance-based design. The principles of Axiomatic Design can be seen to formalize the concept of systems engineering and provide a prescriptive methodology for selecting an optimal solution alternative. The resulting design methodology is a consistent framework for attacking performance-based design problems at various levels of abstraction.

2.2 Axiomatic Approach to Performance-Based Design

Systems engineering [8,17,21,28,47] is a general problem-solving paradigm that divides the decision-making process into a series of stages, and these stages are typically outlined as follows: problem identification, formalization of goals, generation of solution concepts, evaluation of concepts and selection of the best solution, and implementation. Templeman [47], for example, defines the transition across these stages as a sequence of four fundamental questions whose answers lead to the selection of an optimal solution:
1. What are the goals that must be achieved?
2. How are the goals achieved, limited, and related to one another within each solution alternative?
3. How are solution alternatives assessed in terms of good and bad?
4. How can the best solution be identified?

Implementation of the systems approach relies on hierarchical decomposition of a problem into sub-problems, and the generate-and-evaluate process is invoked iteratively at each level of the hierarchy, [28]. Thus, a system concept is initially identified to satisfy an overall set of requirements. This initial concept is then partitioned into sub-systems, components, and interfaces that must be configured so as to satisfy the original set of requirements plus any sub-requirements related to serviceability, ease of manufacture, and maintenance, [8]. Without a formal strategy for partitioning and evaluating solution alternatives, it is difficult to advance directed, comprehensive solutions because there is no mechanism to prevent the designer from trying to force-fit traditional concepts.

Axiomatic Design [42-45] also defines the design process as a hierarchical activity where solutions are based on a sequence of stages pertaining to problem definition, solution synthesis, solution evaluation, and implementation. However, the advantage of Axiomatic Design versus traditional systems engineering is the fact that the decomposition and decision-making processes are made explicit by the following key concepts:

1. Existence of different design domains.
2. Definition of the decomposition process in terms of a zig-zagging between design domains.
3. Requirement that the best solution satisfies certain design axioms.

Firstly, the transition from an abstract statement of need to a physical entity is not linear but cyclical, depicted as a helix [20,43]. Successful transition requires continuous exchange of knowledge between and within different design domains. These domains are shown in Figure 2-1. Problem identification corresponds to a customer's statement of needs and occurs in the client domain. In the development of single-item products, such as constructed facilities, the client or his agent takes an active role: a) initiate the order for the project, b) express desired performance requirements, and c) establish project cost constraints. In the manufacture of mass-produced products, the client domain refers to a market of consumers, and their active input is often provided by proxy in the sales or product-planning sections of the manufacturing organization. In either case, designers also use the client domain as a buffer for gaining an understanding of their particular tasks and for reasoning about the functional requirements for subsequent design stages or subordinate design disciplines.

The output from the client domain is then translated in the functional domain into a combination of objective and subjective goals or functional requirements (FRs). In an office development project, for example, leasable space is often specified as an objective requirement related to economic feasibility and aesthetic properties are subjective criteria to promote tenant interest. Starting with the stated FRs, the design engineer generates a solution by defining design variables ( DVs) so as to satisfy the FRs and describe the solution's physical make-up. This process of synthesizing a design solution constitutes a mapping between
FIGURE 2-1.  DESIGN DOMAINS
the functional and physical domains. In turn, the DVs generated in the physical domain are interpreted as a set of requirements for implementation in the process domain. The engineer responsible for designing a construction plan or a manufacturing process plan maps these requirements to a sequence of actions or process variables (PVs) to effect a result.

Secondly, the concept of decomposition refers to the fact that the output of each design domain evolves from abstract to concrete ideas in a top-down or hierarchical manner. The FRs for a design project are decomposed into a hierarchical structure of sub-objectives. The total design description at any level of the hierarchy consists of all components, attributes, and relationships needed to satisfy the stated sub-objectives. Various sources [20,21,24,34] recognize that the mapping process must take place over a number of levels of abstraction so as to define sufficient design data to support construction or manufacturing activities. For example, Hubka [20] recommends typically six levels of design detail, while Pahl and Beitz [34] identify three.

In some systematic approaches to design [20,21,24,34], the conceptual design stage involves decomposition of the overall functional requirement(s) into an appropriate set of sub-functions, followed by a one-to-many mapping between each sub-function and feasible function carriers. Solution concepts are obtained from the synthesis of various function carriers into composite structures or layouts. The feasible solutions are then detailed during the succeeding stages of design refinement in order to support the original sub-functions and to satisfy other design requirements, such as durability, aesthetics, and ease of production.

In Germany, for instance, widespread acceptance of systematic
design methods has led to the promulgation of standardized design procedures [34,50]. These procedures enable selection of suitable combinations of functional elements by including catalogs of known approaches for solving particular product functions. They also facilitate component detailing by providing standardized guidelines and design details. Since much of the systematic design method as espoused by the German school [34,50] focuses on achieving product function, design for ease of production is postponed until late in the design process and involves the use of standardized guidelines and design details.

Axiomatic Design also recognizes that the mapping between functional requirements and design variables must take place over a number of levels, yet Suh's text [43] stipulates that functional decomposition is continuous and precedes the generation of design variables at all levels of abstraction. Thus, the reasons for concept refinement during the later design stages are made explicit. In addition, design for ease of construction or ease of manufacture is considered concurrently because the hierarchical decomposition in one domain cannot be performed independent of the evolving hierarchies in the other domains, [43]. As a result, prior to decomposing a parent set of FRs, the FRs must be mapped successfully to a set of DVs, and these DVs must be mapped, in turn, to an appropriate set of PVs. Thus, the decomposition and mapping activities correspond to a zig-zagging between the functional, physical, and process domains as shown in Figure 2-2.

Continuously zig-zagging through the process or construction domain is a robust strategy for advancement of buildable solutions. It allows concurrent development of design and construction plans. In addition, the constructibility of the project can be reviewed in terms of the required systems and
FIGURE 2-2.  HIERARCHICAL STRUCTURE AND ZIG-ZAGGING
activity sequences, rather than relying on the detailed calculation of the man-hour and material expenditures necessary for constructing the discrete building elements. The latter approach to improved constructibility is a sub-optimization scheme, and empirical studies [18] have indicated that reliance on such elemental approaches does not significantly reduce total construction costs.

In the absence of a design-build environment that supports concurrent design and construction planning, the enforcement of constructibility as a performance criterion requires the designer to perform the zig-zagging through the process planning domain. Thus, educating designers in the area of basic construction operations and promoting designer-based constructibility evaluations are vital for achieving the progress demanded by a competitive industry [18]. The Business Roundtable, for example, estimates the value of the cost benefits derived from improved constructibility to be 10 to 20 times the cost of the additional design investment [12].

Lastly, the most important concept in Axiomatic Design is the existence of design axioms which provide a rational basis for the evaluation of proposed solution alternatives and the subsequent selection of the best solution. The first axiom focuses on the mapping between "what is required" (FRs or DVs) and "how do we achieve it" (DV$s or PV$s). The second axiom establishes information content as a relative measure for comparing alternative solutions. The axioms may be stated in the following procedural form [43]:

AXIOM 1 The Independence Axiom
In an acceptable design, the mapping between the FR$s and DV$s is such that each FR can be satisfied without affecting any other FR$s.
AXIOM 2  The Information Axiom

Among all proposed solutions that satisfy Axiom 1, the most optimum design has the minimum information content.

The intent of the design axioms is to allow explicit, objective reasoning about the merit of each proposed design solution and the identification of the best solution from among many alternatives. As a result, Axiomatic Design offers a mathematical model for systems engineering that transforms Templeman's [47] aforementioned strategy of fundamental questions into the following systematic and quantitative methodology:

1. Synthesize design variables to satisfy goals.
2. Identify relationships among the variables and goals.
3. Evaluate solution alternatives via design axioms.
4. Choose the best solution per Axioms 1 and 2.

The implications of the design axioms with respect to the design of constructed facilities are discussed below in Sections 2.3 and 2.4.

ILLUSTRATIVE EXAMPLE: The following simple example demonstrates the concepts of multiple design domains and hierarchical decomposition based on zig-zagging between domains.

Introduction: In the building delivery process, the owner or developer, through discussion with an architect, articulates his needs. The architect then translates these needs into FRs by preparing a brief for the building, [36]. Although the client usually does not state explicit needs pertaining to structural strength and serviceability, their provision is implicit and forms the core of the structural engineer's functional requirements. In addition, the
structural engineer derives constraints from the functional layouts provided in both the architectural brief and any conceptual sketches. The structural engineer tries to satisfy his objectives by specifying DVs in the form of framing materials, structural elements, geometric configurations, and dimensions.

The contractor is a design agent within the process domain, and his goal is to construct the building according to the design specifications. As a result, the structural engineer's output defines a portion of the requirements for construction process planning. The subsequent design of the construction plan satisfies these requirements by selecting and scheduling a series of construction systems, procedures, and equipment.

**Perceived Needs:** A design is being developed for an open car park (by BOCA code [11] definition, "open" means at least 50% open at each floor on at least two sides) with a reinforced concrete frame. The National Parking Association [32] recommends that perimeter barriers be provided to resist a static horizontal load of 10,000 lbs. applied 18 inches above the floor at any point. Therefore, a perimeter barrier must be integrated into the car park design.

**Problem Definition:** The problem definition in the functional domain is expressed in terms of a functional requirement and a constraint.

**FR1 =**

Provide a perimeter barrier capable of resisting a static horizontal load of 10,000 lbs. applied 18 inches above the floor at any point.

**Constraint =** The car park's structural frame is reinforced concrete.
Constraints differ from FRs in that they establish hard boundaries or limits that must be satisfied by all admissible solution alternatives, [43]. In this example, the constraint, the car park's structural frame is reinforced concrete, means that any proposed solution must be compatible with reinforced concrete construction.

Choice of DVs: Having defined a set of FRs and constraints in the functional domain, a set of DVs for the perimeter barrier must next be selected to conceptualize a solution in the physical domain. Since the design is constrained by the a priori decision to use a reinforced concrete frame, some type of reinforced concrete beam spanning between the structure's perimeter columns is a possible solution.

\[ DV_1 = \text{Reinforced concrete beam elements spanning between perimeter columns.} \]

Choice of PVs: There are two construction alternatives in the process domain for accomplishing DV1: cast-in-place concrete construction or precast concrete beam elements. Without completing this mapping between DV1 and the process domain, FR1 cannot be decomposed properly into lower level requirements. The lower level requirements must be derived from the selected mode of action. For example, further detailing of the cast-in-place alternative is primarily concerned with satisfying strength criteria. In addition to strength criteria, the design requirements for precast construction, on the other hand, must include provisions to ensure that member lengths and field connection devices are adaptable to deviations in both column location and plumbness because precast elements must be ordered in advance of field construction activities. The design and process planning hierarchies corresponding to a conceptual description of
cast-in-place and precast beam elements are shown in Figure 2-3.

2.3 The Independence Axiom

The mapping of requirements into values for the design variables during design synthesis can be viewed as a matrix transformation. Defining \((FR)\) as the generalized vector containing the functional requirements, and \((DV)\) as the design variables vector, the matrix transformation is expressed as

\[
(FR) = [A] (DV)
\]  

(2-1)

where \([A]\) is the "design matrix" that defines the relationships between the design variables and the design requirements. The structure of \([A]\) determines whether or not the proposed design maintains the independence of the individual requirements.

If \([A]\) is a diagonal matrix (a square matrix whose non-diagonal entries are zero) as shown in Equation (2-2), then a change in requirement \(FR_i\) necessitates a change in only one design variable \(DV_i\). This design condition satisfies Axiom 1 and is defined as an uncoupled design.

\[
\begin{bmatrix}
FR1 \\
FR2 \\
FR3
\end{bmatrix} = \begin{bmatrix}
A11 & 0 & 0 \\
0 & A22 & 0 \\
0 & 0 & A33
\end{bmatrix} \begin{bmatrix}
DV1 \\
DV2 \\
DV3
\end{bmatrix}
\]  

(2-2)

On the other hand, when the design matrix \([A]\) consists of mostly non-zero entries, the design is termed a coupled design. Consider the following three-dimensional case where \([A]\) is fully populated.
FIGURE 2-3. DESIGN AND CONSTRUCTION PROCESS PLANNING HIERARCHIES FOR CONCEPTUAL DESCRIPTION OF CAST-IN-PLACE AND PRECAST CONCRETE BARRIERS
\[
\begin{align*}
\{ \text{FR1} \} &= \begin{bmatrix} A11 & A12 & A13 \\ A21 & A22 & A23 \\ A31 & A32 & A33 \end{bmatrix} \{ \text{DV1} \} \\
\{ \text{FR2} \} &= \{ \text{DV2} \} \\
\{ \text{FR3} \} &= \{ \text{DV3} \}
\end{align*}
\] (2-3)

Any change in requirement FR1 cannot be satisfied by simply changing DV1. The presence of the off-diagonal terms A21 and A31 indicates that changes to DV1 must also affect the design's response with respect to requirements FR2 and FR3, and Axiom 1 is violated. The solution must rely on the convergence of an iterative strategy. The physical significance of a coupled design is that the resultant product is not flexible to change. The design has poor adaptability because it is difficult or impossible to adjust for any variations in requirements due to uncertainties such as loading changes, construction tolerances, and material degradation due to weather.

When \([A]\) is a triangular matrix (all entries either above or below the main diagonal are zero), the design is said to be quasi-coupled or decoupled. A decoupled design is represented by the following design equation:

\[
\begin{align*}
\{ \text{FR1} \} &= \begin{bmatrix} A11 & 0 & 0 \\ A21 & A22 & 0 \\ A31 & A32 & A33 \end{bmatrix} \{ \text{DV1} \} \\
\{ \text{FR2} \} &= \{ \text{DV2} \} \\
\{ \text{FR3} \} &= \{ \text{DV3} \}
\end{align*}
\] (2-4)

The independence of the individual requirements (FR) is maintained by defining the DVs in a specific sequence. Firstly, FR1 is satisfied by specifying an appropriate value for DV1. The designer then evaluates DV2 in order to satisfy FR2 without affecting FR1. Lastly, FR3 is satisfied by evaluating DV3 without compromising FR1 and FR2. In any other sequence, the functional requirements cannot be satisfied independently, the design behaves in a coupled manner, and Axiom 1 is violated.
In addition to uncoupled and decoupled designs, redundant design is a third classification that satisfies the Independence Axiom. A redundant design occurs when there are more DVs than requirements and each requirement can be independently satisfied by varying one or more design variables, [43]. Equation (2-5), for example, is a redundant design because changes in requirement FR1 can be satisfied by changing either DV1 or DV3 without affecting the status of FR2.

\[
\begin{align*}
\begin{bmatrix}
\text{FR1} \\
\text{FR2}
\end{bmatrix} &= 
\begin{bmatrix}
A11 & 0 & A31 \\
0 & A22 & 0
\end{bmatrix} 
\begin{bmatrix}
\text{DV1} \\
\text{DV2} \\
\text{DV3}
\end{bmatrix} \\
&= \text{(2-5)}
\end{align*}
\]

A key aspect of a redundant design is the fact that its design matrix can be converted to an uncoupled or decoupled form through manipulation of the redundant design variables. For example, combining DV1 and DV3 into a dimensionless group reduces the number of DVs in Equation (2-5) to two, and the corresponding design matrix expresses a one-to-one mapping between the vectors (FR) and (DV). Setting DV1 or DV3 equal to a constant value is an alternative approach for reducing Equation (2-5) to an uncoupled design.

The principle of maintaining the independence of the functional requirements is supported by the mathematical concepts of controllability and observability in general systems theory and control theory [25,33]. Considering the output of a system to be a function of its state variables, the properties of controllability and observability are defined as follows [33]:

A system is controllable if any given initial state can be transferred to any final state by suitable choice of input.
A system is observable if a knowledge of its output vector and input vector is sufficient to determine the system's initial state uniquely.

The property of controllability ensures that the input variables can independently effect changes in the state of a system. Observability implies that changing the state of a system from time $t_0$ to time $t_1$ ($t_1 > t_0$) is path independent. Kalman et al. [25] argue that controllability and observability are necessary and sufficient conditions for system control problems to make sense and have a solution. Consequently, any well-designed system should demonstrate these properties.

In the domain of constructed facilities, the success of many widely used structural concepts is due to the fact that these solutions are controllable and observable; that is, they maintain the independence of functional requirements. The structural steel W-shape and the reinforced concrete beam are examples of beam sections that rely on separate elements for resisting the bending moments and shearing forces necessary for equilibrium. The flanges of the W-shape resist a significant portion of the bending moments while the primary objective of the web area is to transfer shear. Similarly, the design of the moment-resisting longitudinal reinforcing steel for a reinforced concrete beam has been traditionally uncoupled from the design of the member's shear reinforcement.

Iyengar [23] cites the flexibility of the equivalent tube lateral-load system for its success in responding to irregular site geometries, diverse multiple-use requirements, and changing aesthetic considerations. The equivalent tube system relies on the building's perimeter structure of columns and girders to resist wind and seismic forces. The
desired structural effect is for the building's overall length and width to simulate the behavior of a three-dimensional cantilever beam which is an effective lateral-load resisting form for modern, non-prismatic building cross-sections, [23]. Locating the lateral load system on the building's exterior maintains the independence of the building's lateral load and usage requirements because the interior column-and-slab systems must only support vertical gravity loads. Thus, the equivalent tube system offers the flexibility of vertically stacking various floor systems to accommodate different occupancies such as parking, commercial, office, and residential.

Structural engineering also has a long history of reliance on redundant designs. The appeal of a redundant design is the fact that redundancy often provides a means for improving reliability, [43]. Rigid frames with diagonal bracing elements, termed braced frames, are an example of a redundant structural concept. The flexural resistance of the columns and the truss-action created by the diagonal bracing members provide two load paths for lateral load resistance. Consequently, braced frames are popular in seismic design applications because their redundancy inhibits progressive structural collapse during a severe earthquake. A fault-tolerant shear wall is an alternative to a braced frame offering a one-to-one mapping between FRs and DVs, yet it is difficult to design and construct an economical shear wall that matches the inherent reliability of the braced frame.

**ILLUSTRATIVE EXAMPLE:** The following example discusses the cantilever beam shown in Figure 2-4 and illustrates the use of Axiom 1.

**Problem Definition:** The design of the beam is governed by functional requirements pertaining to strength and
a) ELASTIC DESIGN
\[
\begin{align*}
\begin{bmatrix} \sigma \\ \delta \end{bmatrix} &= 
\begin{bmatrix} x & x \\ 0 & x \end{bmatrix}
\begin{bmatrix} d \\ I \end{bmatrix}
\end{align*}
\]
DECOUPLED

b) PLASTIC DESIGN
\[
\begin{align*}
\begin{bmatrix} \sigma \\ \delta \end{bmatrix} &= 
\begin{bmatrix} x & 0 \\ 0 & x \end{bmatrix}
\begin{bmatrix} z \\ I \end{bmatrix}
\end{align*}
\]
UNCOUPLED

c) RECTANGULAR CROSS-SECTION
\[
\begin{align*}
\begin{bmatrix} \sigma \\ \delta \end{bmatrix} &= 
\begin{bmatrix} x & x \\ x & x \end{bmatrix}
\begin{bmatrix} d \\ b \end{bmatrix}
\end{align*}
\]
COUPLED

FIGURE 2-4. AXIOMATIC DESIGN OF A CANTILEVER BEAM
serviceability, i.e. bending stress and deflection.

FR1= The bending stress shall not exceed $\sigma$.
FR2= Vertical deflection under applied load shall not exceed $\delta$.

These requirements are then mapped to a set of design variables associated with cross-sectional properties.

Choice of DVs: If one chooses to define a solution in terms of values for the beam's moment of inertia $I$ and depth $d$, for example, the design matrix for elastic design is triangular and the appropriate first step would be to establish $I$. This approach corresponds to "designing for stiffness". If plastic design is assumed, selecting the beam's moment of inertia $I$ and plastic modulus $Z$ as design variables reduces $[A]$ to diagonal form and appropriate values for $I$ and $Z$ can be established independent of each other. If a rectangular cross-section is assumed, however, selecting beam depth $d$ and beam width $b$ as the design variables couples the requirements on bending stress and deflection. The requirements cannot be satisfied independently and the Independence Axiom is violated.

2.4 The Information Axiom

The Independence Axiom provides a first-pass criterion for synthesizing feasible solutions. The capabilities of each proposed product or process design that satisfies Axiom 1 must next be compared with the governing set of requirements until the designer identifies an optimum result. Without a numerical basis for comparison, however, the final selection of a design solution involving many functional requirements can only be made on an ad hoc basis. The ability to quantify how well a proposed design satisfies the governing
requirements provides a rational means for selecting the best solution.

To reason effectively about a proposed design, one must recognize the probabilistic nature of the output from the design variables. Consider the design of a manufacturing process that machines a part from bar stock [43]. Most machine tools have a broad range of tolerances associated with their output, making it difficult to obtain a specific value consistently (see Figure 2-5). If the amount of overlap between the part's specified design tolerance and a machine's tolerance range is small, the probability of obtaining the desired tolerance is low and the production of an acceptable part may be preceded by the wasteful production of many unacceptable parts. Therefore, the best design strategy is to maximize the probability of success, i.e., either select a machine with a tolerance range that is within the specified design tolerance or, if possible, increase the specified design tolerance.

Information Theory, as advanced by Shannon [39], provides a basis for quantifying the probability of success of design decisions. Information Theory is a mathematical theory of electronic communication in which the message source in a communication system is considered to be of a probabilistic nature. The information content associated with any message generated by the message source is defined as the logarithm of the inverse of its probability of occurrence p [39].

\[ I = \log_2 \left( \frac{1}{p} \right) \text{ binary digits} \tag{2-6} \]

Shannon's measure relates the information content of a message to its mathematical uncertainty. This is a natural definition because the certain transmission and reproduction of messages is a fundamental concern in communications. The
FIGURE 2-5. RELATIONSHIP BETWEEN DESIGN RANGE AND MACHINE TOLERANCE
more that is known about which message a source will produce, the less is the amount of uncertainty, and the less is the amount of information required for a receiver to reproduce the message.

Earlier sections have discussed the concept of design synthesis as a mapping process between functional requirements and design variables. This transformation corresponds to reproducing the functional requirements in terms of physical embodiments that are peculiar to each designer. Therefore, Shannon's notion of information content is extensible to the problem of achieving the stated functional requirements, i.e., a design's functional requirements can be viewed as message sources. Consequently, Equation (2-6) provides an accounting system for representing a design's probability of success so that an overall measure, reflecting the contributions of many different requirements can be obtained. The use of information content for evaluating design decisions is appealing because it captures the impact of uncertainty and offers a homogeneous and non-dimensional approach to the evaluation of multi-objective design problems: all functional requirements are viewed in terms of their probability of success. In addition, the information content for a sequence of independent variables, as in the case of an uncoupled design, is given by the simple sum of the information measures for the separate variables.

Information content also provides rational decision criteria for exchanging design knowledge across disciplines. Each designer advances his design goals in a unique design language. For example, the language of an architect is very much different from that of a structural engineer, and neither of these two disciplines has much in common with the language of the contractor. In fact, these communication barriers are often cited as contributing to the lack of
effective integration in the development of constructed facilities, [46]. Information content provides a vehicle for expressing each group's decisions in terms of their impact on project goals. Thus, the binary digit or bit becomes a currency for negotiation among all participants.

2.5 Example: Axiomatic Design of Structural Frame for Mechanical Parking Structure

In this section, the use of Axiomatic Design [43] will be illustrated using a structural design problem.

2.5.1 Introduction

In response to the congestion of motor vehicles that plagues both urban centers and suburban commercial areas, many state and local building codes have imposed parking restrictions on all new development projects. These regulations mandate the provision of a number of off-street parking spaces based on the area of developed space. Providing the necessary parking capacity through surface parking lots, garages, or underground parking, however, subtracts from the total space available for use as leasable operating space. Although the actual area of parking stalls varies from about 100 to 200 sq. ft., traditional parking facilities for small developments require an average area of about 300 sq. ft. per parking space, [51]. This increased area includes the driving corridors that are necessary to access the facility and the individual parking stalls. Consequently, a parking system is needed that provides storage capacity in a reduced amount of space.
2.5.2 Problem Definition

The problem definition in the functional domain is expressed in terms of a set of functional requirements.

FR1= Provide a number of parking spaces using less than 300 sq. ft. per parking space.

FR2= Provide access to each space.

Having defined requirements (FR1,FR2) in the functional domain, a set of DVs must next be selected to conceptualize a solution in the physical domain.

2.5.3 Physical Solution

In response to the need to improve parking density, an entrepreneur recently developed and patented a design for a mechanical parking system, [6]. Since parking systems that rely on mechanical means to transport vehicles to and from parking spaces have been in use for a number of years, the merit of the new system is the fact that the entire parking garage acts as an elevator. This convention reduces the area necessary to access the facility and the individual parking stalls by eliminating the need for an internal network of driving corridors. A concept sketch of the parking system based on a 24-car capacity is shown in Figure 2-6.

The structure consists of a vertical array of levels. The concept of a vertical array of parking spaces is analogous to the use of skyscrapers to provide office and residential space in congested urban centers. The width of the garage is sufficient to accommodate one car length (overall dimension = 20 to 25 feet), two cars can be parked between each pair of columns (centerline dimension of columns = 20
Figure 2-6. Concept Sketch of Mechanical Parking System
to 25 feet), and the garage's overall length is a function of the number of parking spaces per level. Figure 2-6 corresponds to six cars per level and a total capacity of 24 cars. A set of hydraulic pistons raise and lower the parking structure providing access to each parking level from a central concourse.

At the system level, the cited solution can be described by the following set of design variables:

\[ DV_1 = \text{Movable structure with vertical array of parking spaces.} \]

\[ DV_2 = \text{Hydraulic lifting system consisting of vertical pistons and the system to generate the hydraulic pressure.} \]

The corresponding design equation is an aid for identifying whether this concept compromises the independence of FR1 and FR2.

\[
\begin{bmatrix}
\text{FR1} \\
\text{FR2}
\end{bmatrix} =
\begin{bmatrix}
X & 0 \\
X & X
\end{bmatrix}
\begin{bmatrix}
DV_1 \\
DV_2
\end{bmatrix}
\quad (2-7)
\]

Equation (2-7) describes the mapping between FRs and DVs in a Boolean manner: X denotes a strong functional dependence and 0 denotes a weak dependence or no dependence at all. The lower triangular structure of the 2x2 design matrix indicates that the proposed mechanical parking system is a decoupled design and satisfies Axiom 1. For an assumed parking capacity, the matrix is not diagonal because the hydraulic system (DV2) must be capable of sustaining the permanent deadweight of the structure. The pistons' stroke or length of travel also must be sufficient to ensure that all parking levels are accessible from the central concourse. Therefore, the proper design sequence is to first design a structure
with the requisite parking capacity. The deadweight and dimensions of the structure are then input to the design of the hydraulic lifting system.

The original, patented solution [6], defined by DV1 and DV2, can be modified by the addition of a system of counterweights to balance the permanent deadweight of the structure.

\[
\begin{align*}
\text{DV1} &= \text{Movable structure with vertical array of parking spaces.} \\
\text{DV2} &= \text{Hydraulic lifting system.} \\
\text{DV3} &= \text{System of counterweights to balance deadweight of structure, excluding vehicular loads.}
\end{align*}
\]

\[
\begin{pmatrix}
\text{FR1} \\
\text{FR2}
\end{pmatrix} = 
\begin{bmatrix}
X & 0 & 0 \\
X & X & X
\end{bmatrix}
\begin{pmatrix}
\text{DV1} \\
\text{DV2} \\
\text{DV3}
\end{pmatrix}
\tag{2-8}
\]

The addition of DV3 serves to uncouple the permanent deadweight of the structure from the lifting capacity of the hydraulic pistons, yet FR1 and FR2 are still quasi-coupled because design of the lifting system so as to access all parking levels depends upon the height of the structure. Equation (2-8) represents a redundant design because FR2 can be controlled by adjusting both the capacity of the lifting system and the amount of counterweight.

Since the design alternatives described by Equations (2-7) and (2-8) (Options 1 and 2, respectively) both satisfy the Independence Axiom, the Information Axiom must be used to identify the best solution. For both options, the information content related to satisfying FR1 is quite small when compared to the value associated with FR2 because the probability of failure for the structure is quite small compared to the probability of malfunctioning for the lifting
system due to mechanical wear or a power failure. By limiting the discussion to FR2 and assuming a given structure DV1, one can argue qualitatively that redundancy improves the reliability of the system, thereby reducing the information content. Thus, the reliability of Option 2 is greater than that of Option 1 due to the following reasons:

1. Reduced buckling potential of the extended piston.
2. Reduced energy input for operation.

2.5.4 First-Order Decomposition

Decomposition of FR1 and FR2 establishes design requirements for the parking structure, hydraulic lifting system, and subsurface construction, but the scope of the remainder of this example will be limited to axiomatic design of the parking structure.

The purpose of the parking structure is to provide a structural platform for the safe parking of vehicles. It must have sufficient structural integrity to resist the anticipated vertically-acting and laterally-acting loads without compromising car park operation. The vertically-acting loads are live loads, due to usage and snow, combined with the deadweight of the parking structure. Laterally-acting loads or overturning effects are caused by wind and eccentric parking of automobiles. Since the parking structure is movable and the pistons are axial elements incapable of resisting lateral shear, the functional requirements must include provisions for global restraint of the suspended structure, i.e., a system is needed to restrain rigid body motions of the structure due to lateral effects.

In addition to offering safe operation, the proposed parking
system must be cost-competitive versus traditional parking facilities. The weight of the structural platform impacts both its material procurement costs and its construction labor costs because construction cost estimates are typically derived from material take-offs from the contract drawings. The deadweight of the structural platform also impacts the material and labor costs for the counterweight system. Therefore, the designer can control a sizeable portion of the total construction cost by imposing the need for a lightweight, cost-competitive structure as a functional requirement. At the current level of physical detail, the weight and associated construction cost of any proposed structural solution cannot be established a priori. Rational functional requirements, however, can be developed by consideration of structural mechanics and the identification of a reasonable cost reference.

Structural systems typically satisfy their strength and stiffness requirements through a skeletal, 3-dimensional grid of bending and axial elements. Table 2-1 summarizes the key parameters for strength-based and stiffness-based design of beam and axial members for minimum weight. These parameters are derived in Appendix A. Table 2-2 gives characteristic values for mass density-to-strength ratio $\rho/\sigma$ and mass density-to-stiffness ratio $\rho/E$ for a variety of materials: structural steel, reinforced concrete, wood, aluminum, and high-performance composites such as carbon-fiber reinforced polymers (CFRP) and glass-fiber reinforced polymers (GFRP). This data is extracted from Reference 7 and is assumed to represent system ranges for uniform probability distributions. For a lightweight structure, the corresponding design specification is chosen by the designer to be roughly the lower 20% of the total range of values listed in Table 2-2: 2.3 to 25 kg/MN-m for $\rho/\sigma$ and 8 to 45 kg/GN-m for $\rho/E$. 

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### TABLE 2-1. MATERIAL PROPERTY PARAMETERS FOR OPTIMIZING STRUCTURAL ELEMENT WEIGHT (FROM APPENDIX A)

<table>
<thead>
<tr>
<th>Element</th>
<th>Strength-Based</th>
<th>Stiffness-Based</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending</td>
<td>$\rho/\sigma$</td>
<td>$\rho/E$</td>
</tr>
<tr>
<td>Axial</td>
<td>$\rho/\sigma$</td>
<td>$\rho/E$</td>
</tr>
</tbody>
</table>

$\rho =$ Material density  
$\sigma =$ Strength  
$E =$ Elastic modulus
<table>
<thead>
<tr>
<th>Material</th>
<th>Density $\rho$ (kg/m$^3$)</th>
<th>Yield Strength $\sigma$ (MN/m$^2$)</th>
<th>Elastic Modulus $E$ (GN/m$^2$)</th>
<th>Unit Cost $\rho_C$ ($/kg$)</th>
<th>$\rho/\rho_C$ (kg/MN-m)</th>
<th>$\rho/E$ (kg/GN-m)</th>
<th>Cost $\rho_C\times(\rho/\rho_C)$ ($/MN-m$)</th>
<th>Cost $\rho_C\times(\rho/E)$ ($/GN-m$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>7800</td>
<td>248-400</td>
<td>196-200</td>
<td>0.453</td>
<td>19.5-31.5</td>
<td>39.0-39.8</td>
<td>8.83-14.3</td>
<td>17.7-18.0</td>
</tr>
<tr>
<td>Concrete</td>
<td>2500</td>
<td>25-70</td>
<td>45-50</td>
<td>0.290</td>
<td>35.7-100</td>
<td>50.0-55.6</td>
<td>10.4-29.0</td>
<td>14.5-16.1</td>
</tr>
<tr>
<td>Wood</td>
<td>400-800</td>
<td>35-55</td>
<td>9-16</td>
<td>0.431</td>
<td>11.4-14.5</td>
<td>44.4-50.0</td>
<td>4.91-6.25</td>
<td>19.1-21.6</td>
</tr>
<tr>
<td>Aluminum</td>
<td>2700</td>
<td>40-627</td>
<td>69-79</td>
<td>2.33</td>
<td>4.31-67.5</td>
<td>34.2-39.1</td>
<td>10.0-157</td>
<td>79.7-91.1</td>
</tr>
<tr>
<td>GFRP</td>
<td>1400-2200</td>
<td>100-300</td>
<td>7-45</td>
<td>3.30</td>
<td>7.33-14.0</td>
<td>48.9-200</td>
<td>24.2-46.2</td>
<td>161-660</td>
</tr>
<tr>
<td>CFRP</td>
<td>1500-1600</td>
<td>640-670</td>
<td>70-200</td>
<td>198</td>
<td>2.34-2.39</td>
<td>8.00-21.4</td>
<td>463-473</td>
<td>158-424</td>
</tr>
</tbody>
</table>

**Design Range**

- $2.3-25$
- $8-45$
- $0-50.8$
- $0-31.5$
Table 2-2 also includes cost per unit mass density for each material. Normalized cost data for comparison of materials is generated by multiplying the unit material costs by their associated mass density-to-strength ratios $\rho/\sigma$ and mass density-to-stiffness ratios $\rho/E$. This yields cost data in terms of specific cost per unit strength and stiffness ($\rho*\rho/\sigma$ and $\rho*\rho/E$). Again, the specific cost ranges are assumed to reflect uniform probability distributions.

Typical construction costs for parking garages in New England range from $8000 to $12,000 per parking space, [48]. Although these prices refer to static structures constructed of reinforced concrete and/or structural steel, they provide a good reference for establishing a design specification. Figure 2-7, extracted from Reference 51, depicts the tradeoffs among surface lots, garages, and underground parking as a function of land cost (data reflects 1989 dollars). For land values above $60 per square foot, underground parking facilities are more economical than either surface lots or a parking structure consisting of one supported level. The construction cost at which the proposed elevator-type parking system becomes economical versus an underground facility of equivalent capacity can be calculated from the following formula that is modified from Weant and Levinson [51]:

$$C_1 < (L + V)[(A_2/N_2) - (A_1/N_1)] + C_2 \quad (2-9)$$

where:

- $C_1 =$ Construction cost per space, proposed elevator-type system.
- $C_2 =$ Construction cost per space, underground facility = $15,000.
- $A_1 =$ Average square feet per space, proposed elevator-type system = 250.
FIGURE 2-7. TRADEOFFS AMONG PARKING FACILITIES AS A FUNCTION OF LAND COST
(WEANT AND LEVINSON, [51])
A2 = Average square feet per space, underground facility = 300.

N1 = Number of parking levels for 24 cars, proposed elevator-type system = 4.

N2 = Number of parking levels for 24 cars, underground facility = 1.

L = Land cost = $60 per square foot.

V = Parking space value in terms of leasable operating space = $150 per square foot (estimated at 2.5 times land cost)

Equation (2-9) indicates that a construction cost of less than about $65,000 per parking space is required for the proposed system to be economically feasible. The required cost of the parking structure is about 1/3 of $65,000 or $21,000 per parking space if a three-way cost split is assumed among the parking structure, hydraulic lifting system, and the combined counterweight and subsurface systems. This $21,000 cost estimate corresponds to 1.75 times the maximum cost of $12,000 per parking space for typical construction. Therefore, the design specification for specific cost is chosen to be from 0 to 1.75 times the maximum tabulated specific cost values between structural steel and reinforced concrete, i.e., 0 to 50.8 $/MN-m for cost as a function of strength and 0 to 31.5 $/GN-m cost as a function of stiffness.

FR1 is decomposed as follows:

FR11 = Lightweight, cost-competitive structure per the following specification:
\[ \rho/\sigma, \text{ design range= 2.3 to 25 Kg/MN-m} \]
\[ \rho/E, \text{ design range= 8 to 45 Kg/GN-m} \]
\[ \rho_c/\sigma, \text{ design range= 0 to 50.8 $/MN-m} \]
\[ \rho_c/E, \text{ design range= 0 to 31.5 $/GN-m} \]
FR12 = Structural integrity to sustain lateral loads.
FR13 = Structural integrity to sustain vertical loads.
FR14 = Restrained rigid body, lateral motion of parking platform.

The corresponding design variables are generalized below:

DV11 = Material selection.
DV12 = Structural framing to resist lateral loads.
DV13 = Structural framing to resist vertical loads.
DV14 = Guideway system.

The associated design equation is given by Equation (2-10).

\[
\begin{bmatrix}
\text{FR11} \\
\text{FR12} \\
\text{FR13} \\
\text{FR14}
\end{bmatrix} = 
\begin{bmatrix}
X & 0 & 0 & 0 \\
X & X & 0 & 0 \\
X & 0 & X & 0 \\
0 & X & 0 & X
\end{bmatrix}
\begin{bmatrix}
\text{DV11} \\
\text{DV12} \\
\text{DV13} \\
\text{DV14}
\end{bmatrix}
\quad (2-10)
\]

The design expressed by Equation (2-10) is decoupled because the number of DVs equals the number of FRs and the non-zero elements of the design matrix create a triangular pattern. The proper design sequence per Axiom 1 is to select first a structural material and then to define an appropriate structural framing pattern. The guideway system DV14 should then be designed for compatibility with the parking structure's lateral framing DV12.

2.5.4.1 Selection of Structural Material, DV11

Joint consideration of strength, stiffness, and cost creates a multi-objective optimization problem that must be resolved. Consequently, information content (Axiom 2) can be used to select the optimal structural material from among the set of feasible alternatives. Equation (2-6) defines the information content of a design decision as the base 2
logarithm of the inverse of its probability of success. The probability of success \( p \) for a proposed solution concept is obtained through integration of the overlapping areas between the design range and the probability distribution that characterizes concept capability. For concepts described by a uniform probability distribution (see Figure 2-8), the integration reduces to the following simple expression:

\[
p = \frac{\text{Common Range}}{\text{System Range}} \tag{2-11}
\]

The resulting information content is given by:

\[
I = \ln_2 \left( \frac{1}{p} \right) = \ln_2 \frac{\text{System Range}}{\text{Common Range}} \tag{2-12}
\]

Evaluation of the information content for each candidate material involves calculating the probabilities of success associated with satisfying the desired mass density-to-strength ratio \((\rho/\sigma)\), mass density-to-stiffness ratio \((\rho/E)\), and specific cost according to Equation (2-11); substituting the respective probability values into Equation (2-12) to obtain information measures; and then summing these information measures to obtain the total information. The optimal material is selected on the basis of the minimum total information. Individual and total information measures are summarized in Table 2-3 for each of the candidate materials. Structural steel has the minimum information content and, therefore, is the optimal material choice. Thus,

\[
DV11 = \text{Structural steel}.
\]
FIGURE 2-8. PROBABILITY OF SUCCESS ASSOCIATED WITH UNIFORM DISTRIBUTION FUNCTION
<table>
<thead>
<tr>
<th>Material</th>
<th>Strength $\rho/\sigma$ (bits)</th>
<th>Stiffness $\rho/E$ (bits)</th>
<th>Cost $\rho_c \times (\rho/\sigma)$ (bits)</th>
<th>Cost $\rho_c \times (\rho/E)$ (bits)</th>
<th>Total Information (bits)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>1.13</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>1.13</td>
</tr>
<tr>
<td>Concrete</td>
<td>*</td>
<td>*</td>
<td>0.0</td>
<td>0.0</td>
<td>*</td>
</tr>
<tr>
<td>Wood</td>
<td>0.0</td>
<td>3.22</td>
<td>0.0</td>
<td>0.0</td>
<td>3.22</td>
</tr>
<tr>
<td>Aluminum</td>
<td>1.61</td>
<td>0.0</td>
<td>1.85</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>GFRP</td>
<td>0.0</td>
<td>*</td>
<td>0.0</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>CFRP</td>
<td>0.0</td>
<td>0.0</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

* denotes $I=\log_2(1/0)$
2.5.4.2 Selection of Lateral Load-Resisting Frame System, DV12

Specification of a frame system to resist lateral load involves the selection of member layouts so as to obtain satisfactory load response while satisfying constraints associated with vehicle access. Two common structural steel systems for resisting lateral loads are shown in Figure 2-9. Trusses are structural systems that are arranged specifically to carry loads at their joints. As a result of this convention, the joints are pin connections and the members primarily behave as axial elements with little bending. This mode of action results in relatively slender, lightweight members.

Removal of the diagonal bracing elements that characterize truss construction requires the addition of moment-resisting joints between the members in order to provide a mechanism for lateral stability. The resulting structure is called a "rigid frame." For rigid frames, lateral loads produce flexural effects that are transmitted through the joints so that bending is distributed to all members of the framework. The use of rigid frames requires deeper and heavier members than does the use of braced frames of comparable load capacity and stiffness because the rigid frame members are principally subjected to cross-sectional bending. An advantage of rigid frame construction, however, is the open space between the columns.

The car park must be framed to resist lateral loads acting in two orthogonal directions, i.e., both parallel and perpendicular to the direction of parking. Since diagonal bracing would obstruct the right-of-ways required for vehicle access, orthogonal sets of braced and rigid frames are selected for lateral load resistance. A plan view of the
FIGURE 2-9. STRUCTURAL STEEL SYSTEMS FOR LATERAL LOAD RESISTANCE
The proposed structural system is shown in Figure 2-10. Thus,

\[ DV12 = \text{Orthogonal sets of trusses and rigid frames.} \]

Lateral resistance along the front of the parking structure is provided by rigid frame construction so as to accommodate vehicle access. Rigid frame construction is also specified along the back of the structure in order to provide a symmetric configuration for resisting lateral effects in the longitudinal direction. Trusses are acceptable for transverse lateral resistance because there are no accessibility constraints between parking bays.

2.5.4.3 Selection of Gravity Load-Resisting Framing System, DV13

As shown in Figure 2-6, the parking structure is partitioned into an array of twelve bays, and each bay accommodates two vehicles. The column spacings for the bays are about 20 to 25 ft. and the gravity loads are on the order of 100 lbs. per sq. ft. This situation corresponds to a short-span, medium load system [41], and the selected framing pattern is shown in Figure 2-11. Therefore,

\[ DV13 = \text{Short-span, medium load framing.} \]

2.5.4.4 Layout of Guideway System, DV14

The elements of the guideway system are located at the four corners of the parking structure. This configuration is chosen for the following reasons:

1. Guides should be placed at column locations to transmit effectively lateral load effects from the truss and rigid frame systems.
FIGURE 2-10. LAYOUT OF STEEL FRAMING SPECIFIED FOR LATERAL LOAD RESISTANCE
FIGURE 2-11. PLAN VIEW OF STEEL FRAMING FOR GRAVITY LOAD RESISTANCE
2. Use of two guides, one at each end of the structure, would conflict with the hydraulic pistons.

3. Use of guides at intermediate columns would interfere with ease of access.

The guideway consists of stationary upright rails supported by pillars. The functions of the rails and pillars are to guide the structure in its vertical travel, to prevent tilting of the structure due to lateral forces, and to transmit the lateral forces from the suspended structure to the supporting foundation. Locating the guideway system at the corners of the structure requires the lateral loads resisted by the interior framing to be reacted through the end columns. Therefore, the lateral-load resisting systems also must include diagonal bracing in the plane of the floors and roof so as to provide diaphragm-action for distribution of lateral loads through the structure. Thus,

DV14= Set of four guide rails with supporting pillars.

The completed first-order decomposition of the parking structure's design is summarized below.

FR11= Lightweight structure:
  \( \rho/\sigma \), design range= 2.3 to 25 Kg/MN-m
  \( \rho/E \), design range= 8 to 45 Kg/GN-m
  \( \rho_c*\rho/\sigma \), design range= 0 to 50.8 \$/MN-m
  \( \rho_c*\rho/E \), design range= 0 to 31.5 \$/GN-m
FR12= Structural framing to sustain lateral loads.
FR13= Structural framing to sustain vertical loads.
FR14= Restrain rigid body, lateral motion of parking platform.

DV11= Structural steel.
DV12= Orthogonal sets of rigid frames and trusses
       (including diagonals for diaphragm action).
DV13= Short-span, medium load framing.
DV14= Set of four guide rails with supporting pillars.
The resulting design equation is given by Equation (2-13).

\[
\begin{bmatrix}
\text{FR11} \\
\text{FR12} \\
\text{FR13} \\
\text{FR14}
\end{bmatrix} =
\begin{bmatrix}
X & O & O & O \\
X & X & X & O \\
X & O & X & O \\
O & X & O & X
\end{bmatrix}
\begin{bmatrix}
\text{DV11} \\
\text{DV12} \\
\text{DV13} \\
\text{DV14}
\end{bmatrix}
\] (2-13)

The modified design matrix still satisfies Axiom 1, but a non-zero term has been added to show the existence of coupling between FR12 and FR13 through DV13. This term indicates that members of the floor framing are included in the rigid frame and truss systems, and these members must also contribute to the transfer of laterally-acting loads. Equation (2-13) does neglect the element of the design matrix that couples FR12 and FR13 via DV12 despite the fact that rigid frames can be viewed as coupled systems. This convention recognizes that the additional framing steel required to resist lateral effects for a building structure of this height (equivalent to about a three-story building) is not much greater than that required for vertical loads only, [13]. Thus, the rigid frame concept is quasi-coupled for low levels of lateral load.

2.5.5 Second-Order Decomposition

The design process must zig-zag back into the functional domain in order to establish detailed functional requirements for the design of member cross-sections. The lateral-load resistance of the rigid frame, for example, is decomposed into three sub-requirements:

- **FR121**: Limit maximum lateral deflection of frame.
- **FR122**: Maintain column stresses within allowable limits.
- **FR123**: Maintain girder stresses within allowable limits.
Allowable stress design is assumed to govern member capacity, and a serviceability requirement for lateral deflection is obtained from the Safety Code for Elevators and Escalators [5].

The selected DVs are:

\begin{align*}
DV121 &= \text{Stiffness of guide system pillars, } I_p. \\
DV122 &= \text{Stiffness of columns, } I_c. \\
DV123 &= \text{Stiffness of girders, } I_g. \\
DV124 &= \text{Depth of column sections, } d_c. \\
DV125 &= \text{Depth of girder sections, } d_g.
\end{align*}

Equation (2-14) presents the corresponding mapping between FRs and DVs.

\[
\begin{pmatrix}
FR121 \\
FR122 \\
FR123
\end{pmatrix} =
\begin{bmatrix}
X & X & X & O & O \\
X & X & X & X & O \\
X & X & X & O & X
\end{bmatrix}
\begin{pmatrix}
I_p \\
I_c \\
I_g \\
d_c \\
d_g
\end{pmatrix}
\]  

(2-14)

The arguments made in the selection of the DV set and the writing of Equation (2-14) are:

1. The lateral stiffness of the parking system and the subsequent distribution of reaction forces reflect the stiffness of the guide system coupled with those of the rigid frame's components.

2. The basic variables \((I_c, d_c)\) and \((I_g, d_g)\) are sufficient to define the section modulus and to approximate the cross-sectional area of rolled steel wide-flange sections (commonly referenced as W-shapes).

Equation (2-14) is a redundant design because there are more DVs than FRs and a decoupled 3x3 sub-matrix for controlling the FRs can be partitioned from the 3x5 design matrix, [48]. The redundancy can be removed by setting any two elements of the following subset of DVs to a constant value: \((I_p, I_c, I_g)\).
The girder's moment of inertia $I_g$, for example, also controls the vertical deflection of the floor under gravity loads. Design of the gravity framing system conforms to the Safety Code for Elevators and Escalators [5] and includes a serviceability requirement on floorbeam deflection. This requirement limits floorbeam deflection to $1/960$ of its span as a means to control vibrations due to the moving of cargo on and off elevators. Inclusion of this deflection limit as a constraint to the frame design problem enables removal of $I_g$ from the active set of design variables.

The lateral stiffness of the guide system $I_p$ can also be set to a constant value. Review of standard steel sections tabulated by the American Institute of Steel Construction [4] indicates that the maximum available moment of inertia is 20,300 in$^4$, which corresponds to a W36X300 section. As a result,

$$I_p = 4 \text{ pillars } \times 21,000 \text{ in}^4/\text{pillar} = 84,000 \text{ in}^4 \quad (2-15)$$

is probably a practical limit on the total sum stiffness $I_p$ for the four pillars that comprise the guide system.

Equation (2-16) presents the reduced design equation and the associated constraints. The column stiffness $I_c$ remains as the only parameter that the designer can vary so as to satisfy FR121.

$$\begin{bmatrix} \text{FR121} \\ \text{FR122} \\ \text{FR123} \end{bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & 0 & X \end{bmatrix} \begin{bmatrix} I_c \\ d_c \\ d_g \end{bmatrix} \quad (2-16)$$
Constraint 1 = Girder stiffness $I_g$, based on maximum deflection under gravity load of $1/960$ of span.

Constraint 2 = Prescribed guide system design: $I_p = 84,000 \text{in}^4$.

Implementation of Equation (2-16) relies on a mathematical model of a plane frame coupled to an upright cantilever beam of stiffness $I_p$. The model is comprised of 2-dimensional beam elements. Rollers provide the linkage between the elements of the frame and guide. Values for $I_p$ and $I_g$ are specified in compliance with the constraint conditions. Lateral shear forces due to wind and an overturning moment due to eccentric vehicle parking are applied to the model, and input values for $I_c$ are varied until the lateral deflection criteria is satisfied. The resulting reaction forces and member moments are then used to establish values for section depths, $d_c$ and $d_g$.

Once values for $I_c$, $d_c$, and $d_g$ are computed, candidate sets of rolled steel W-shapes are identified. For each proposed column or beam section, information content (Axiom 2) is used to measure the degree of satisfaction of the governing 2-tuple $<I_c, d_c>$ or $<I_g, d_g>$. The resulting rigid frame design consists of W14X53 columns and W10X22 girders.

2.5.6 Comparison With Other Structural Design Methods

The traditional design procedure [13] for defining the member proportions of a rigid frame system is based on the following sequence of steps that correspond to a stress-based design:

1. Gravity loads due to deadweight, usage, and snow are calculated for frame members using tributary areas. Lateral loads are also determined by approximate
techniques such as the portal frame method.

2. Initial values are established for column and beam proportions by considering the combined effects of gravity and lateral loads.

3. Resulting member proportions are then input to a more rigorous mathematical model and analyzed for lateral stiffness. Analyses are iteratively performed with varying member properties until acceptable deflections are obtained.

4. Reaction forces and member end moments derived from the lateral load analysis are used to check whether members satisfy strength requirements, and appropriate revisions are made. Lateral deflection of the revised design is then confirmed.

Based on Equation (2-14), one can see that the above solution procedure is the inverse of that established by Axiom 1. Advantage is not made of the decoupled structure of the design matrix, and the solution depends on the convergence of an iterative scheme. Consequently, the above, traditional, iterative four-step procedure must be enhanced by an optimization strategy that reviews the efficiency of the member proportions in terms of total steel weight. In fact, Reference 13 explicitly advocates such a two-stage approach.

The design procedure derived from axiomatic design, on the other hand, is similar to the concept of dynamic programming which is a technique for structural optimization, [10,26,37,40]. Dynamic programming is a multi-stage approach to problem solving, and it is based on Bellman’s principle of optimality [10]: "An optimal policy (or set of decisions) has the property that whatever the initial state and initial decision are, the remaining decisions must constitute an
optimal policy with regard to the state resulting from the first decision. Thus, both axiomatic design and dynamic programming exploit the serial nature of structural systems so that a problem that requires the joint optimization of n variables is transformed into a sequential optimization scheme involving n sub-problems.
2.6 References


Chapter 3 Attributes of Performance

3.1 Introduction

The development of facilities that satisfy multiple needs requires the ability to reason about total facility performance. The Information Axiom [43] offers the concept of information content as a homogeneous method for evaluating design capability with regard to satisfying functional requirements. For a given design solution, a constituent measure of information content can be determined with respect to each functional requirement. The constituent measures can then be summed to produce a total measure of suitability, and this cumulative measure provides the designer with a quantitative means for comparing the relative merit of competing design schemes.

Use of the Information Axiom, however, requires explicit, quantitative functional requirements and a probabilistic expression of a design alternative's anticipated system range. Therefore, the objective of this chapter is to present a framework for prescribing functional requirements for the delivery of constructed facilities. Various functional requirements are defined, as well as appropriate techniques for quantifying system range.

Since the specification of functional requirements is dependent upon the performance requirements identified in the client domain, a taxonomy of performance requirements or attributes is first presented. The proposed taxonomy of performance requirement is based on the work of Billington [13] regarding critical analysis of constructed facilities. Billington [13] expresses the value of a facility in terms of three meanings: scientific, social, and symbolic. Within
each meaning, diverse attributes of performance, such as
durability and ease of construction, are identified. These
attributes are then mapped to functional requirements, and
rational techniques are offered for quantifying system
ranges. The following section outlines the proposed taxonomy
of performance requirements.

3.2 Taxonomy of Performance Attributes

Chapter 2, including the principles of Axiomatic Design [43],
outlines a systematic methodology for managing the project
development process. One facet of the proposed
performance-based methodology is a hierarchical expression
of the owner's needs or desired performance in the client
domain. Since the precise combination of performance
requirements providing optimum satisfaction to the owner may
be difficult to elicit, a universal or transcendent model of
performance can offer practical guidance.

One such model has been advanced by Billington [13].
Billington's framework for critical analysis of constructed
facilities involves evaluating a facility with respect to
each of the following classes of interpretation:

1. Scientific meaning.
2. Social meaning.
3. Symbolic meaning.

The scientific meaning refers to the shelter and services
that a facility provides. It is defined by quantifiable
properties, such as serviceability, reliability, durability,
and safety. The social meaning captures the project's impact
on society and involves economic, political, and community
factors. Performance requirements in this area can be
partially quantified through consideration of project costs,
demands on construction labor and material resource, and environmental demand.

A structure's symbolism is the most difficult meaning to quantify because it refers to the visual image of the facility and is derived from the aesthetic values of the designers, owners, and general community. Billington [13] divides the symbolic meaning into three categories of visual form: unified, daring, and complex. Since symbolic meaning can only be expressed through verbal analysis [13], aesthetic attributes are considered beyond the scope of this chapter.

Figure 3-1 outlines a taxonomy of performance requirements (PRs) based on Billington's framework. Top-down traversal of the tree provides a systematic method for articulating desired facility performance. However, established methods for defining each PR as a functional requirement and measuring system ranges are necessary to make the concept of performance-based design operational. For example, reliability as a functional requirement must be linked with a set of operations for its measurement. This argument is similar to Bridgman's view [14] that concepts become operational when they are synonymous with a corresponding set of operations, e.g., the concept of length is defined when the operations for measuring length are stated.

The next section establishes operational definitions for the following performance requirements:

1. Reliability.
2. Durability.
4. Maintainability.
5. Constructibility.
7. Environmental Demand.
FIGURE 3-1. TAXONOMY OF PERFORMANCE REQUIREMENTS
(BILLINTON, [13])
3.3 Operational Definitions of Performance

3.3.1 Reliability

Reliability is defined as the probability of a product offering satisfactory performance over a specified period of time, [28]. In the manufacturing industry, product reliability is usually expressed as mean time between failure (MTBF) or the probability of failure per unit time (which is the reciprocal of MTBF), [11]. Although any convenient unit of time can be specified, e.g., hours, days, or years, product reliability refers to periods of effective operation. Thus, the reliability of a constructed facility can be defined as the probability that the facility will be able to provide shelter and services throughout the course of its intended service life, [22].

Consumers of automobiles, computers, appliances, etc., became concerned with product reliability as repair and loss of service became expensive. Japanese automotive manufacturers, for example, targeted improved product reliability versus that of their American counterparts as a strategic means to secure market share and gain competitive advantage, [28]. Yet this notion of product reliability has lagged in the construction industry, despite the fact that the loss of value due to failure is often incalculable. Consider the design and construction of a new bridge. Although the cost of materials and labor necessary for future replacement of the bridge's physical structure can be estimated, it is much more difficult to quantify the cost to society associated with an unanticipated loss of service.

During the early stages of design, the concept of reliability is strongly tied to serviceability. That is, designers
should select those solution concepts with the highest probability of satisfying the stated usage requirements. Once an appropriate solution concept is selected, subsequent design and detailing decisions must ensure that the solution provides satisfactory operation throughout a specified period of service.

The structural reliability of a building form, for example, is derived from a network of horizontally and vertically spanning subsystems that accumulate and transmit loads to the foundation system, [33]. Horizontal subsystems (floors and roofs) gather and transfer vertically-acting dead and live loads to the elements of the vertical subsystems (columns and walls). Floors and roofs also act as diaphragms for distributing horizontally-directed loads, such as wind loads, to those portions of the vertical subsystem capable of transferring lateral shear to the foundation. Thus, the vertical subsystem transfers all loadings to the building's foundation system.

Figure 3-2 is extracted from Schodek [39] and depicts approximate span ranges for a variety of horizontally spanning subsystems. This data can be used for rational selection of structural concepts for floor and roof systems. Once a concept is selected, its components and connections are proportioned so as to satisfy code-based reliability criteria, as well as serviceability requirements related to deflections, vibrations, etc.

Historically, the design of structural components and connection details had been based on a deterministic, allowable strength approach to reliability. In general terms, design for allowable strength involves comparing a nominal estimate of design loads $Q$ to a nominal measure of component resistance $R$. To compute the resistance of a
FIGURE 3-2. SPAN RANGES FOR HORIZONTALLY-SPANNING SYSTEMS (SCHODEK, [39])
structural component, a characteristic cross-sectional or
gEometric property, A, is multiplied by an allowable stress
σall. Reliability of the component requires the product
R = A*σall to be greater than or equal to the design load Q, i.e.,

\[ R - Q \geq 0 \]  

(3-1)

Current design philosophy, however, recognizes the fact that
both component resistances and anticipated loads are variable
quantities, randomly distributed about their nominal values,
[35]. Consequently, both the component resistance R and
applied load Q can be expressed in terms of probability
density functions as shown in Figure 3-3. The corresponding
criterion for evaluation of structural reliability is still
given by Equation (1) but R and Q represent probabilistic
functions, rather than deterministic values.

Given the probability density functions that describe R and
Q, we can define a new function [34]:

\[ Y = R - Q = \text{Safety Margin} \]  

(3-2)

with mean \( \mu_Y \) and standard deviation \( \sigma_Y \). This new function is
plotted in Figure 3-4. The probability of failure \( P_f \) can be
identified graphically as the shaded portion of Figure 3-4.
Mathematically, \( P_f \) is a function of the number of standard
deviations between \( \mu_Y \) and zero. The corresponding ratio
\( (\mu_Y/\sigma_Y) \) is referred to as the reliability index \( \beta \).

\[ \beta = \mu_Y/\sigma_Y = \text{Reliability Index} \]  

(3-3)

Design codes [1,2] have adopted a load and resistance factor
format in order to simplify the use of a probabilistic
approach to structural reliability. The designer starts with
FIGURE 3-3. DISPERSION OF APPLIED LOAD Q AND COMPONENT RESISTANCE R
FIGURE 3-4. CONCEPT OF SAFETY MARGIN
the calculation of nominal values for component resistance \( R_n \) and applied loads \( Q_n \). These nominal values are then modified by the use of factors that approximate the probability that the actual resistance is less than \( R_n \) and the actual loads are greater than \( Q_n \). The governing reliability criterion is given by:

\[
\phi R_n - \gamma Q_n \geq 0
\]  

(3-4)

where resistance factor \( \phi < 1 \) and load factor \( \gamma > 1 \). For design codes, the implicit reliability index \( \beta \) ranges between 3 and 4 [35] and corresponds to a probability of failure of order 1 in 10,000. Thus, \( 3 \leq \beta \leq 4 \) is a suitable functional requirement for reliability-based design of new structural products.

3.3.2 Durability

Durability is a measure of product life that refers to how much service the consumer receives prior to failure of the product by physical degradation, [20]. Therefore, the durability of a product can be measured by its service life. The corresponding functional requirement prescribes the desired service life in the form of a design range.

For constructed facilities, design for durability involves the following considerations [32]:

1. Selection of building materials suitable for the desired service life with respect to environmental exposure.

2. Design and detailing of components and connections so as to prevent premature deterioration.
Durability-based design involves the selection of appropriate building materials on the basis of their long-term behavior under the expected degradation conditions. Table 3-1, for example, is extracted from Reference [37], and it summarizes order of magnitude service life data for various building materials and exposure conditions. Data of this kind provide a rational basis for material selection with respect to a desired service life.

Subsequent use of the selected building material or materials in the design of building elements requires an understanding of the possible modes of deterioration. Avoidance of these degradation modes can be prescribed as functional requirements governing the detailed design of components and connections. The designer must try to satisfy explicitly each of these requirements by specifying key material parameters, configuring components and connections, and adding design elements, such as expansion joints and protective coatings.

One difficulty associated with designing facilities so as to satisfy durability criteria is the lack of a systematic mechanism for synthesizing the considerable volume of available research data into a usable design package, [21]. In particular, a template is needed to help identify essential durability considerations for evolving designs. Institute TNO for Building Materials and Building Structures [22], for example, has compiled a checklist to aid in the identification of potential failure modes. This list contains 64 possible hazards to the service life of a facility divided among the following headings:
### TABLE 3-1. ORDER OF MAGNITUDE SERVICE LIFE DATA

(PIHLAJAARA, [37])

<table>
<thead>
<tr>
<th>Materials</th>
<th>Class of Degradation Factors and Expected Age</th>
<th>Age in Years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 Very Severe Exposure¹</td>
<td>2 Severe Exposure²</td>
</tr>
<tr>
<td>Precious metals</td>
<td>1 000 to 10 000</td>
<td>100 000</td>
</tr>
<tr>
<td>Strong natural rocks</td>
<td>100 to 1 000</td>
<td>1 000 to 10 000</td>
</tr>
<tr>
<td>Natural rocks</td>
<td>10 to 100</td>
<td>100 to 1 000</td>
</tr>
<tr>
<td>Strong ceramic materials</td>
<td>100 to 1 000</td>
<td>1 000 to 10 000</td>
</tr>
<tr>
<td>Ceramic materials</td>
<td>1 to 100</td>
<td>100 to 1 000</td>
</tr>
<tr>
<td>High-strength concrete</td>
<td>10 to 100</td>
<td>100 to 1 000</td>
</tr>
<tr>
<td>Concrete</td>
<td>1 to 100</td>
<td>50 to 500</td>
</tr>
<tr>
<td>Mortars</td>
<td>1 to 10</td>
<td>10 to 100</td>
</tr>
<tr>
<td>Gypsum</td>
<td>...</td>
<td>1 to 10</td>
</tr>
<tr>
<td>Metals (for example, iron)</td>
<td>1 to 10</td>
<td>10 to 100</td>
</tr>
<tr>
<td>Wood</td>
<td>1 to 10</td>
<td>10 to 100</td>
</tr>
<tr>
<td>Plastics</td>
<td>1 to 10</td>
<td>10 to 50</td>
</tr>
<tr>
<td>Paints</td>
<td>...</td>
<td>2 to 20</td>
</tr>
<tr>
<td>Leather</td>
<td>1</td>
<td>10 to 50</td>
</tr>
<tr>
<td>Vestiges of natural fibers</td>
<td>...</td>
<td>1 to 10</td>
</tr>
<tr>
<td>Bone, hair</td>
<td>10 to 100</td>
<td>100 to 1 000</td>
</tr>
</tbody>
</table>

¹Frost, snow, ice, thawing, great changes in temperature and humidity, erosion, dissolution, strong sunlight, pollution, conditions with strong corroding effects, for example, seawater, polluted water, corroding chemicals, etc.

²Average variable outdoor conditions, moderate changes in freezing and thawing.

³Moderate temperature, dry, slight changes in environment.

⁴Dry, very slight ventilation, low temperature, no sunlight, constant conditions.
1. External influences.
2. Properties of the structure (material and geometry).
3. Limit states.
4. Damage criteria.
5. Special effects (uncertainties in design and construction, maintenance and repair).

Although the checklist of 64 hazards is not exhaustive, it does assist durability-based design. Viewing each potential hazard as a load $Q$ acting on the physical system, mathematical models for material resistance $R$ can be developed from research findings concerning the time-dependent behavior of materials and physical systems. The use of stochastic methods to model the time-dependent changes in system and material properties under the influence of the so-called loads permits transformation of the durability evaluation into an equivalent reliability prediction. Specifically, failure occurs at time $t$ if

\[ R(t) - Q(t) < 0 \]  \hspace{1cm} (3-5)

where $R(t)$ is the probabilistic resistance of the system at time $t$ and $Q(t)$ is the simultaneous load. When $R(t)$ and $Q(t)$ are monotonic functions of time, the equality $R(t)=Q(t)$ can be used to establish the service life associated with a particular mode of failure, [22]. The design objective is to control the parameters contributing to $R(t)$ so that the desired service life is attainable.

Application of Equation (3-5) to durability-based design has been demonstrated in the literature for the case of an elevated, reinforced concrete slab [41]. Corrosion of the steel reinforcement due to carbonation of the concrete cover was considered as the governing mode of failure. A mathematical model for carbonation of the concrete and the initiation of corrosion was obtained from the research
community, and parameters pertaining to concrete mix design, slab cross-sectional details, and corrosion data for the reinforcement were included in the model. Although the ensuing probabilistic analyses were very approximate, the results provided a rational basis for reasoning about the relative merits of increased concrete cover versus the use of protective rebar coatings as a means to achieve a 60-year service life.

3.3.3 Safety

There are three or more safety concerns associated with the use and operation of a physical system [11]:

1. Protection of the system itself.
2. Protection of the systems with which it interfaces.
3. Protection of users, bystanders, or the environment.

In the first case, the system must be protected from or be able to sustain critical exposure to forces, temperatures, and other external effects that may curtail its ability to provide service. This disruption can occur either suddenly or gradually with time.

The second concern addresses the potential for the operation of one system to threaten the serviceability of other systems. Mechanical vibrations, for example, can produce a fatigue failure within the supporting structural frame. Another example is the fact that buildings constructed adjacent to one another can pound against each other during an earthquake.

Lastly, many physical systems can pose a threat to humans and/or the environment. One such threat is the potential for loss of life or property damage due to physical collapse.
Complex physical systems also involve the potential for uncontrolled discharge of lethal voltages, electromagnetic radiation, and corrosive and/or carcinogenic chemicals and vapors, [11].

Designers of constructed facilities rely on building codes [15] and certain governmental regulations [18,19] to establish the functional requirements necessary for safety. Fire safety considerations are a strong determinant in the development of most state and local building regulations, [39]. The BOCA National Code [15], for example, restricts the permissible height, story number, and floor area of a proposed facility according to the specified type of construction and the anticipated level of fire hazard.

Table 3-2 is extracted from Reference 15, and it establishes minimum fire resistance ratings for the walls, partitions, structural elements, floors, ceilings, roofs, and exits for five types of construction. The tabulated resistance values refer to how the various structural sub-systems and elements must perform with respect to standardized ASTM fire resistance tests [9]. Thus, the data in Table 3-2 provide quantitative criteria for classifying the type of construction for a proposed facility. Some prescriptive, fire-resistant, design criteria derived from past practice and laboratory testing are available for conventional materials, such as structural steel, reinforced concrete, and timber. In addition, the functional requirements presented in Table 3-2 provide a rational basis for implementing new configurations and materials.

3.3.4 Maintainability

Design for maintainability seeks to minimize the effort and
### TABLE 3-2. MINIMUM FIRE RESISTANCE RATINGS FOR VARIOUS TYPES OF BUILDING CONSTRUCTION

<table>
<thead>
<tr>
<th>Structure element</th>
<th>Type 1 Section 402.0</th>
<th>Type 2 Section 402.0</th>
<th>Type 3 Section 404.0</th>
<th>Type 4 Section 406.0</th>
<th>Type 5 Section 408.0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Noncombustible</td>
<td>Noncombustible</td>
<td>Combustible</td>
<td>Noncombustible</td>
<td>Combustible</td>
</tr>
<tr>
<td>1. Exterior walls</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2. Fire walls and party walls (Section 807.3)</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3. Fire separation Assemblies (Section 808)</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>4. Fire partitions (Section 910.2)</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>5. Dwelling unit separations (Sections 909.3, 913.3 and Notes 1 and 2)</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>6. Smoke barriers (Section 912.8 and Notes 1)</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>7. Other nonbearing partitions</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>8. Interior bearing walls, bearing partitions, consoles, girders, trusses (other than roof trusses) and framing (Section 912.3)</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>9. Structural members supporting walls (Section 912.8 and Notes 1)</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>10. Roof construction excluding beams (Section 913.3 and Notes 1)</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>11. Roof construction excluding beams, trusses and framing across and roof deck (Section 914.8 and Notes 1)</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
<td>Not less than</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**Notes:**
- **Note a.** For fire resistance rating requirements for structural members and assemblies which support other fire resistance rated members or assemblies, see Section 912.1.
- **Note b.** For reductions in the required fire resistance rating of exit and shaft enclosures, see Sections 917.11 and 915.3.
- **Note c.** For substitution of other structural materials for timber in Type 6 construction, see Section 1703.1.1.
- **Note d.** For fire resistance ratings of exterior access corridors, tenant separations and dwelling unit separations, see Section 1010.1 and 1010.4.1.
- **Note e.** For exceptions to the required fire resistance rating of construction supporting exit access corridor walls, tenant separation walls in covered mall buildings, and smoke barriers, see Sections 911.4 and 912.2.
- **Note f.** For buildings having habitable or occupable stories or basements below grade, see Section 907.3.1.
- **Note g.** For buildings having habitable or occupable stories or basements below grade, see Section 308.4.
- **Note h.** For Use Group R-3, see Section 308.4.
- **Note i.** For Use Group R-1, see Section 308.4.
- **Note j.** For Use Group R-1, see Section 308.4.
- **Note k.** For Use Group R-1, see Section 308.4.
cost necessary for repair, adjustment, and cleaning of a physical system, [11]. Designers of computer, industrial, and military systems target ease of maintenance as a design objective by focusing on a system’s mean time to repair (MTTR) or life-cycle cost. In contrast, designers of constructed facilities historically neglect maintenance issues, and this neglect has become the rule rather than the exception, [26]. This condition is made more severe by the fact that maintenance and repair costs incurred over the life of a facility are about two to three times the initial capital investment [45]. Thus, design for maintainability has been a lost opportunity for improved economic performance of constructed facilities.

When maintenance issues are considered during the design process, the outcome is not necessarily to the owner’s advantage. For instance, research studies conducted at Heriot-Watt University, Edinburgh [45] indicate that the project architect is the chief agent for considering ease of maintenance during the building design process, and the frequency of the references to maintenance factors increases toward the later, detailed stages of design. The research findings identify two reasons for this latent approach to maintainability.

Firstly, the architects were preoccupied with cost and aesthetic considerations during the early, conceptual stages of planning and design. Secondly, the architects tended to advocate maintenance considerations as an argument against owners’ requests for cost reductions during the later stages of design. The architects relied on a combination of past experience with facility maintenance problems and detailed cost estimates to substantiate their position against cost-cutting changes. These research findings suggest that the early focus on aesthetic factors is gradually replaced
by an expedient concern for maintainability.

The omission of maintenance requirements from the early stages of planning and conceptual design and the lack of a systematic and comprehensive approach to designing for maintainability suggests that the maintenance factors cited by the architects during detailed design are sub-optimal solutions. Consequently, owners should require that the project design team includes their maintenance managers. The maintenance managers are to represent owner interests by formulating requirements for maintainability and contributing to the synthesis and evaluation of design alternatives. Since the average skill level of the maintenance personnel cannot increase with the complexity of the facility [11], maintenance managers must provide the project design team with specific expertise concerning representative maintenance operations.

Based on this model of maintenance operations, the quality of the maintenance environment and the accessibility of the building components are the fundamental considerations for maintainability, [11]. The quality of the maintenance environment refers to the impact of the surroundings on system degradation. For example, open-air facilities, such as car parks, pose special problems with regard to the ponding of water, entrapment of soil and airborne particles, thermal exposure, and natural material degradation.

Accessibility requirements ensure that maintenance personnel and equipment have access to all maintainable features and components. The required access for a particular component is dependent on the nature of the associated maintenance operation. Access requirements for replacing an overhead light bulb, for instance, can be satisfied by providing adequate vertical and horizontal clearances. However,
sliding tracks and hinged mountings may have to be included in the design of access provisions for large service equipment that must be moved for testing and repair, [11].

3.3.5 Constructibility

The Constructibility Committee of the Construction Industry Institute [20] defines constructibility as the optimum integration of construction knowledge and experience in planning, engineering, procurement, and field operations to achieve overall project objectives. The Business Roundtable [17] estimates the cumulative value of the cost benefits derived from improved constructibility in the commercial sector to be 10 to 20% of the total project cost. For the designer, the concept of constructibility emphasizes the development of construction-sensitive designs and the effective communication of engineering information to those groups that are involved in the procurement and construction tasks.

The development of construction-sensitive designs requires an understanding of the practicality of the design descriptions with regard to implementation by construction personnel. Practicality is basically an issue of how compatible the object descriptions are with the available construction materials and methods for fabrication and assembly. Many problems encountered during the construction process can be avoided by designing to known fabrication and erection capabilities, [12].

Design practicality is currently addressed by contractors through value engineering studies. Value engineers seek to optimize total life-cycle costs for a proposed facility without compromising the essential functions. The scope of
value engineering studies is limited to designs that are either completed or in advanced stages of preparation because the cost models rely on significant levels of design detail, [23]. Since value engineering studies are not performed concurrently with design decision-making, the extent of change is limited by project time constraints. A much greater impact can be achieved if constructibility issues are given high priority during the initial project planning and design phase. Figure 3-5 illustrates this point. The return on cost is maximized when design and construction knowledge are integrated and applied simultaneously during the design phase.

While constructibility can be improved by analyzing discrete elements so as to reduce man-hour expenditures, an operational view of construction processes can offer greater benefits, [30]. Operational assessments must be performed within the construction process domain, and they focus on the actual sequence of activities and tasks necessary for construction. Thus, an operational analysis of construction activities requires a systematic mapping of the design variables to an appropriate set of process variables.

Griffith [30] identifies five factors that have considerable influence upon construction operations and constructibility. These factors provide a framework for reasoning about construction operations and developing constructibility measures. The factors are:

1. Complexity of the operational sequence.
2. Level of technical complexity in design detail.
3. Flexibility of the design and allowances for component and trade tolerances.
4. Degree of accuracy in setting out.
5. Inter-relationship level between construction elements.
FIGURE 3-5. ABILITY TO INFLUENCE FINAL COST
(CONSTRUCTION INDUSTRY INSTITUTE, [20])
Complexity of the operational sequence refers to the number of steps required for construction and the logical relationships among the steps. The use of a design matrix to represent the mapping of design variables to process variables provides a mathematical framework for reasoning about operational complexity. Consider the following 3x3 design equation for construction of an arbitrary design element.

\[
\begin{bmatrix}
\{ DV1 \} \\
\{ DV2 \} \\
\{ DV3 \}
\end{bmatrix} =
\begin{bmatrix}
A11 & A12 & A13 \\
A21 & A22 & A23 \\
A31 & A32 & A33
\end{bmatrix}
\begin{bmatrix}
\{ PV1 \} \\
\{ PV2 \} \\
\{ PV3 \}
\end{bmatrix}
\]

(3-6)

where: \( \{ DV \} = \) vector of design variables. 
\( \{ PV \} = \) vector of process variables. 
\([ A ] = \) design matrix that defines mapping.

The structure of \([ A ]\) determines the complexity of the construction sequence. If \([ A ]\) is a diagonal matrix, i.e., \( A_{ij} = 0 \) if \( i \neq j \) and \( A_{ij} = 0 \) if \( i \neq j \), the process plan is defined by a set of three independent and parallel activities as shown in the network diagram of Figure 3-6a. In Figure 3-6a, the event preceding \( PV1 \), \( PV2 \), and \( PV3 \) is a start event because it has no preceding activities, and the end event has no succeeding activities.

If all the entries of \([ A ]\) either above or below the main diagonal are zero, \([ A ]\) is a triangular matrix, and the design is termed quasi-coupled or decoupled, [43]. The following equation defines a decoupled process plan:

\[
\begin{bmatrix}
\{ DV1 \} \\
\{ DV2 \} \\
\{ DV3 \}
\end{bmatrix} =
\begin{bmatrix}
A11 & 0 & 0 \\
A21 & A22 & 0 \\
A31 & A32 & A33
\end{bmatrix}
\begin{bmatrix}
\{ PV1 \} \\
\{ PV2 \} \\
\{ PV3 \}
\end{bmatrix}
\]

(3-7)
a) UNCOUPLED PROCESS PLAN

b) DECOUPLED PROCESS PLAN

c) COUPLED PROCESS PLAN

FIGURE 3-6. NETWORK DIAGRAMS FOR CONSTRUCTION PROCESS PLANNING
The presence of non-zero, off-diagonal terms $A_{21}$, $A_{31}$, and $A_{32}$ establishes the nature of the dependencies between the process activities. The corresponding network diagram is shown in Figure 3-6b. It indicates that completion of each upstream activity is critical for completion of the succeeding downstream activities. Since the queuing time associated with the execution of the process plan increases with the complexity of the operational sequence [30], reduction of the triangular design matrix of Equation (3-7) to a diagonal form would reduce the amount of unproductive time lost to queuing sequential activities.

The following design equation depicts a coupled mapping between $(DV)$ and $(PV)$.

\[
\begin{align*}
\begin{bmatrix}DV1 \\ DV2 \\ DV3\end{bmatrix} &= \begin{bmatrix}A_{11} & A_{12} & 0 \\ A_{21} & A_{22} & 0 \\ A_{31} & A_{32} & A_{33}\end{bmatrix} \begin{bmatrix}PV1 \\ PV2 \\ PV3\end{bmatrix} \\
&= (3-8)
\end{align*}
\]

The corresponding network diagram for Equation (3-8) is shown in Figure 3-6c. The closed loop between PV1 and PV2 is an illogical relationship from a scheduling standpoint because the starting times for the two activities are mutually dependent, [44]. In practice, the loop can be removed by decomposing PV1 and PV2 into sub-activities that can be executed sequentially, albeit an activity sequence involving trial-and-error iterations. Otherwise, removal of the loop requires selection of an alternative set of process variables or re-formulation of the set of design variables.

Once an uncoupled or decoupled operational sequence is defined, constructibility factors such as the technical complexity of the design details, allowances for trade tolerances, and the required degree of accuracy refer to the suitability of the mapping between the design variables and
the process variables. Intuitively, the best design strategy is to select those process variables that have the highest probability of satisfying the design requirements. However, since the scope of possible construction systems and subsystems is limited by cost and available technology, design for constructibility provides a learning mechanism for specifying those design variables that have the highest probability of being satisfied.

Consider the design of a reinforced concrete slab. Although it is difficult to obtain a specific rebar spacing consistently, there is a certain range of standard tolerances associated with the process of rebar placement. Thus, one measure of the practicality of the slab design is the amount of overlap between the specified tolerance for rebar spacing and standard practice (see Figure 3-7). If the amount of overlap is small, acceptable positioning of the rebar may be preceded by a trial-and-error sequence of unacceptable placements.

The concepts of standardization, repetition, and modularity provide a basis for reasoning about the relationships between design variables and construction technology without forcing the designer to assume the role of the contractor, [10]. Standardization involves the use of widely accepted dimensions, tolerances, material specifications, and detailed configurations. High levels of standardization support reliance on less costly, readily-available components and processes rather than customized applications.

Repetition improves the efficiency of construction operations by promoting economy of scale with regards to both the procurement of resources and the execution of activities. The unit cost or time for repetitive activities decreases with frequency of use due to the influence of a learning
FIGURE 3-7. RELATIONSHIP BETWEEN SPECIFIED TOLERANCE AND STANDARD PRACTICE FOR PLACEMENT OF SLAB REINFORCEMENT
curve. Modularity also improves the efficiency of site activities because it allows the clustering of design elements involving multiple assembly steps into larger units. The modules can be assembled either on or off the job site depending upon the available space. Subsequent on-site installation of each module is only concerned with the interface connections between modules, thereby reducing the complexity of site operations.

The fifth constructibility factor identified by Griffith [30] refers to the inter-relationship level between construction elements. The Building Research Establishment’s publication Designing for Production [16] describes the significance of these inter-relationships as follows:

Each separate activity requires the tradesman to transport himself and his tools to the place of work and then away again afterwards. The less work there is involved in each activity, the greater will be the ratio of productive to non-productive time. Also, the greater the number of operations to be performed, the greater the probability of delays occurring, since many of the operations are directly dependent upon previous activities being completed before they begin.

The concept of the Interface Index (as developed in Chapter 4) provides a rational measure for the level of inter-relationships between construction elements. It is an information-based metric derived from graph theory. The Interface Index quantifies the number of couplings that occur when the different subsystems of a project are integrated into a complete system.

3.3.6 Cost

There are various methods for measuring the cost performance of a facility. For example, ASTM Committee E-6 and its
subcommittee on building economics [8] identifies the following methods:

1. Life-cycle cost (LCC).
2. Benefit-to-cost ratio (BCR) or Savings-to-investment ratio (SIR).
3. Internal rates of return (IRR).
5. Payback (PB).

The life-cycle cost method measures the present value total of all relevant costs associated with a facility, including expenditures for design, construction, operation, maintenance, and replacement [5]. The unit measure of cost effectiveness is dollars, and an economically optimal design alternative has the minimum life-cycle cost.

BCR and SIR are numerical ratios whose magnitude expresses the economic value of a decision: the larger the ratio, the more the dollar benefits or savings exceed the project costs [3]. BCR and SIR rely on a comprehensive definition of all costs and benefits (or savings) associated with a facility during a particular time period. The characteristic ratios are simply given by the following expressions:

\[
BCR = \frac{\text{Net Benefit}}{\text{Investment}} \quad (3-9a) \\
SIR = \frac{\text{Net Savings}}{\text{Investment}} \quad (3-9b)
\]

where:

- Net Benefit = difference between present value benefits and costs.
- Net Savings = difference between present value savings and costs.
- Investment = present value investment cost.

IRR is used to determine whether a decision is cost-effective over a particular period of time by converting the present
value of its associated cash flow into an equivalent rate of return on investment [4]. A project is defined as economically attractive if the equivalent rate of return exceeds some minimum acceptable rate.

The net benefit method simply measures the difference between benefits and costs, where both are discounted to present value [6]. Since the unit of measure is dollars, the solution alternative with the highest NB is economically optimal.

Payback predicts the amount of time necessary for a solution alternative to just pay back its initial investment [7]. Calculation of PB relies on comprehensive evaluation of the flow of benefits and costs, where both are discounted to present value. A significant limitation of the payback method is the fact that it does not consider benefits and costs over the remaining service life of a facility. Consequently, it tends to favor short-term projects with a quick payback rather than long-term projects with a longer payback period.

Implementation of cost as a performance requirement requires a description of the governing measurement criterion and the acceptable range of values. Value engineers [23,24], for example, typically rely on life-cycle cost measures for selecting between two or more feasible design solutions. The cost requirement is then included in the definition of the client’s needs, and the subsequent design and construction process plan must be reviewed to ensure compliance. Consequently, an "economic design" [29] of the project must evolve alongside the physical design so as to aid in the evaluation of solution alternatives.

Elemental cost planning is one approach for cost cont
during project planning and design, [27,40]. It is equivalent to treating cost as a functional requirement and consists of the following sequence of activities.

1. Preliminary cost estimate based on elemental estimates and the characteristic area of the facility.
2. Cost plan.
3. Cost checks.
4. Bid reconciliation.
5. Post-contract cost control.

The information flow for the above sequence of activities parallels the traditional flow of design information from conceptual to preliminary to detailed abstractions. The preliminary cost estimate maps the client’s needs to a dollar cost value based on comparison with similar projects and heuristics, [27]. Cost estimates for all anticipated building elements, such as floors, walls, and roofs, are first generated as a function of their expected superficial area. These elemental estimates are then aggregated into a total estimate of project cost. The actual cost limit for the project is then determined by either the owner or the joint action of the owner and designer, [40].

The subsequent stages of cost planning and checking establish cost control by allocating a portion of the total project limit to each building element. The cost plan specifies target costs for each building element, and specific element concepts are then selected so as to comply with the target cost. As design details evolve, more refined element cost estimates are prepared and compared with the cost plan. If the detailed cost estimate exceeds the budget allowance, adjustments must be made to either the element design or the project allocation.

The cost plan should be reconciled with the actual
construction cost once the construction contract is awarded. The reconciliation process seeks to identify and understand the reasons for any substantial differences between the cost plan and the contractor's bid. It is an essential process for the cost estimator to update his historical cost data. Post-contract cost control is often referred to as real-time cost control because it seeks active control of project costs during construction, [27]. Post-contract cost control is most critical if the contract includes provisions that allow the contractor to adjust the contract sum.

Since the accuracy of the elemental cost estimates and the subsequent allocation of project cost to individual building elements are dependent upon past experience, the elemental cost planning is most suitable for routine facility designs where the necessary building systems can be anticipated and historical cost data can be applied, [40]. The design objective tends to shift from "what is the best solution for our client" to "how can we produce a design that is within budget in the allotted time" [27]. Due to expedience, the cost plan may allocate the project budget in a manner that is inconsistent with the unique needs of an owner, resulting in the development of a facility that fails to meet the owner's needs by either overperformance or underperformance. A facility that overperforms wastes resources by providing unnecessary capabilities, and it typically is not the most economical solution because the additional levels of performance are not free; underperformance, on the other hand, negatively impacts use because it fails to satisfy some or all of the owner's performance requirements, [42].

Comparative cost planning is offered as an alternative to the elemental approach outlined above. Where the elemental approach implies designing to cost, comparative cost planning is equivalent to cost estimating the design, [40]. Thus,
total project cost is treated as a constraint that must be checked for compliance when sufficient design information is established. The form of the facility, in terms of its shell, services, elements, and furnishings, is first established so as to satisfy the owner's needs. The cost of the design is then estimated through application of a comprehensive cost model. The advantage of the comparative cost planning is the fact that it does not control design decisions by establishing cost as a functional requirement for each building element, [40]. It permits selection of a combination of feasible design solutions so as to satisfy the established functional requirements, and the sum costs of these alternatives are then compared with the budget constraint. Thus, the designer has an evenhanded basis for balancing diverse functional requirements such as durability, reliability, aesthetics, etc. with cost.

The difficulty with relying on comparative cost evaluations, however, is the significant amount of time required for developing and costing design alternatives until an acceptable solution is found. As a result, the efficiency of both the design and cost estimating processes must be improved. The National Research Council [36] cites the adoption of advanced design methodologies as the fastest way to realize shorter development times, lower costs, and a better match of product performance to the clients' needs. As discussed in Chapter 7, the integration of computer-based tools for information processing within a structured design paradigm, such as Axiomatic Design [43], could provide the means for improving design quality while controlling cost.

3.3.7 Environmental Demand

Three categories of environmental concern can be identified
1. Government prohibition on some potential element of project development.

2. Activities that may require negotiation with cognizant government agencies to establish permissible course of action.

3. Infringement upon a sensitive issue resulting from public opinion, special interest groups, and politically sensitive concerns.

As in any other aspect of performance, design for environmental demand requires a clear distinction between constraints and functional requirements. Constraints are viewed as rigid limits, systemic boundaries that cannot be violated. Consequently, government prohibitions are interpreted as constraints that must be enforced throughout the design and process planning stages. Functional requirements, on the other hand, define the range of desired behavior and can be characterized by a bandwidth of acceptable values, [43]. Therefore, negotiable courses of action and treatment of sensitive issues can be considered functional requirements because there is generally some latitude associated with compliance.

Fabrick and O’Rourke [25] outline a systematic approach for the integration of environmental planning into the traditional framework for project development. The model is outlined in Figure 3-8. It assumes that the environmental planner is brought onto the project as a member of the design team, participating throughout the development life-cycle. The activities presented in Figure 3-8 seek to keep the project on-track with regard to its environmental performance in a manner that is consistent with the type and quantity of information available at each stage of the development process.
FIGURE 3-8. SCHEME FOR INTEGRATING ENVIRONMENTAL PLANNING INTO PROJECT DELIVERY PROCESS (FABRICK AND O'ROURKE, [25]).
The appeal of Fabrick and O'Rourke's strategy [25] is adaptability to the concept of performance-based design. The design agent responsible for environmental performance first acts as a bridge between the client domain and the functional domain during concept formulation. Although the owner has some specific needs that the planned facility must satisfy, explicit project goals and constraints related to environmental performance may be lacking or viewed as a regulatory obstacle to project development. The environmental designer must formulate functional requirements for environmental performance and identify environmental constraints early in the project life-cycle so as to lessen the impact on cost and development time.

Once an overall set of objectives are defined, they must be mapped to a solution concept in the physical domain, and the environmental planner contributes to the synthesis and evaluation of solution concepts. Consistent with the Independence Axiom [43], each functional requirement related to environmental performance must be mapped to a unique design variable in order to maintain the independence of the requirements. The environmental performance of each feasible solution concept is then evaluated in order to provide a rational basis for determining its fidelity in accordance with the Information Axiom [43], as well as for checking regulatory compliance.

Reference 38, for example, presents some formulas for quantifying environmental impact in the following areas:

1. Physical environment.
2. Social environment.
3. Economic environment.
The physical environment refers to both natural surroundings, such as land, air, water, vegetation, and wildlife, as well as the built environment, i.e., infrastructure. Social impacts encompass quality of life considerations, including housing, community facilities, and community services. The economic environment reflects issues related to local employment, income, land values, and the economic base of the area. Figures 3-9 and 3-10 present some of the measures devised to quantify system ranges with respect to the physical and social environments, respectively.

The set of design variables that comprise the optimal solution concept in the physical domain are next mapped into the process domain for implementation. For the environmental designer, this mapping refers to the development of construction procedures that mitigate environmental impact and may require permits and specialized techniques. Regulatory guidelines also contribute constraints to the process plan. The design process then zig-zags back into the functional domain where environmental requirements can be further decomposed for detailed design.

The environmental design for a housing project, for example, may consider the impact of the development on local water quality. Figure 3-9 gives a measure of water pollution impact as the fractional change in the area water quality:

\[
\frac{\text{Water quality in area after project} - \text{Water quality in area before project}}{\text{Water quality in area before project}} \quad (3-10)
\]

Operationally, an acceptable range for fractional change in
### Figure 3.9: Measures of Impact on Physical Environment (RAU, [38])

<table>
<thead>
<tr>
<th>AIR POLLUTION</th>
<th>WATER QUALITY</th>
<th>WILDLIFE VEGETATION</th>
<th>DEMAND ON SEWAGE</th>
<th>DEMAND ON SOLID WASTE SYSTEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>For residential projects:</td>
<td>$\sum_{\text{all pollutants}} \left( \frac{\text{Pollutant emission factor in lb/1000 ft}^2}{\text{Natural gas consumption in 1000 ft}^2 \text{ per dwelling unit}} \right) \left( \text{Number of dwelling units} \right)$</td>
<td>Water quality in area before project</td>
<td>Local wildlife (vegetation) habitat acreage before project</td>
<td>Gal of sewage per capita</td>
</tr>
<tr>
<td>For commercial and industrial projects:</td>
<td>$\sum_{\text{all pollutants}} \left( \frac{\text{Pollutant emission factor in lb/1000 ft}^2}{\text{Gross floor area (GFA) in 1000 ft}^2} \right) \left( \text{Natural gas consumption in 1000 ft}^2 \text{ per 1000 ft}^2 \text{ GLA} \right)$</td>
<td>Water quality in area after project</td>
<td>Local wildlife (vegetation) habitat acreage after project</td>
<td>Gal of sewage per employee</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Water quality in area before project</td>
<td>Local wildlife (vegetation) habitat acreage before project</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Solid waste in pounds per capita</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Solid waste in pounds per employee</td>
</tr>
</tbody>
</table>
FIGURE 3-10. MEASURES OF IMPACT ON SOCIAL ENVIRONMENT (RAU, [38])
water quality is established as a functional requirement and mapped to a corresponding design variable. Basic water quality parameters can be used to quantify the water quality in the building area prior to construction. For each solution alternative, water quality both during and after construction and during use of the completed facility can be predicted by a mathematical model of the system, including the effects of uncertainty. Substitution of the resulting water quality predictions into Equation (3-10) yields a system that must be compared with the required design range. The amount of overlap between the desired change in water quality and the system range corresponds to the probability of satisfying the water quality requirement. The computed probability of success defines the information content of the design with respect to environmental performance in the area of water quality. Environmental performance in other critical areas, such as solid waste disposal and traffic congestion, can be calculated similarly.

3.4 Integration of Performance Criteria Into the Project Development Process

The concept of performance-based design maintains that the primary goal of all members of the project team, e.g., architects, engineers, contractors, and managers, is to satisfy the unique needs of each project. Rather than prescribing uniform specifications for the design and construction of all building systems, subsystems, and components, performance-based design relies on the owner and/or his agents defining the desired performance profile for the facility as a system. It is then the responsibility of the project team to formulate and satisfy the functional requirements for the necessary systems, subsystems, and components.
The first step is to articulate the conceptual needs of the owner as to what the project is about. Is the intent to produce electricity, to provide a viable transportation route, or to simply provide shelter? The project goal must then be mapped to some solution concept in the physical domain. This solution concept fixes the context for decomposing the project goal into a set of functional requirements necessary for the facility to be serviceable. Each functional requirement must then be satisfied and controlled by a unique design variable in the physical domain. Upon completion of this first stage, the design team can create a facility sketch or schematic diagram depicting space allocation and essential equipment.

The schematic diagram establishes the scientific meaning of the facility at an abstract level. Additional design details must be generated in order to convert the abstract model into a functioning, physical system. As a result, the scientific meaning of the facility must be further refined, and both the symbolic and social meanings of the facility must be addressed. The performance attributes defined along the lowest level of Figure 3-1, such as reliability, safety, maintainability, etc., and the operational definitions presented in the Subsections 3.3.1 through 3.3.7 can guide in the formulation of functional requirements pertinent to the detailed design of subsystems and components. As stated previously, the issue of constructibility is best addressed by mapping the generated design variables to construction activities in the process domain.

One appeal of Axiomatic Design [43] is the fact that the components of a functionally uncoupled system can be modeled, characterized, and specified in isolation of how the components are physically situated. However, a design lesson of the 1970’s is the realization that isolated pursuit of one
performance aspect often compromises performance in other areas. For instance, design for energy conservation resulted in a phenomenon known as "sick buildings," i.e., well-insulated facilities with poor air quality and uncomfortable work environments [31]. Consequently, an integrated approach to design evaluation is needed to capture interdisciplinary impacts.

To achieve an integrated solution, it is suggested that the hierarchical mapping of both functional requirements to design variables and design variables to process variables be modeled by a comprehensive design equation of the form:

\[(FR) = [A] (DV)\] (3-11)

where:

\( (FR) = \) vector of functional requirements that specify desired serviceability or behavior.

\( (DV) = \) vector of design variables that describe physical solution.

\( [A] = \) design matrix that identifies nature of mapping.

The structure of the design matrix \([A]\) is determined by assembling the design matrices associated with the various subsystems and components. In addition, group action of the design team is necessary to identify interface issues between subsystems and components. Isolated component models, together with the knowledge of interfaces, establish a rational basis for interdisciplinary evaluation of design quality. The predicted system range of the facility is quantified and compared with the desired range of performance values, and a constituent measure of information content can be calculated. For each design alternative, the constituent measures of information content are summed into an overall
measure of fidelity. This information measure provides a quantitative method for identifying the optimal alternative.

Chapter 5 presents a case study involving evaluation of the design of an existing constructed system according to the above integrated approach. The performance attributes of Figure 3-1, excepting cost and environmental demand, are used to structure functional requirements with regards to the following levels of abstraction:

1. System level.
2. Subsystem level.
3. Component level.

A homogeneous treatment is used at each design level. The Independence and Information Axioms are used to reason about and quantify design quality. Additionally, the concept of an Interface Index, which is developed in Chapter 4, is also used as a quality measure. It quantifies the complexity associated with interfaces arising from integration of the various subsystems and components. The case study demonstrates the following:

1. Use of the concept of performance-based design on a large-scale constructed system.

2. Use of the design axioms and Interface Index as a prescriptive methodology for evaluating and identifying good design.

3. Use of the design axioms and Interface Index as a framework for identifying targets for design and construction innovations.
3.5 References

1. American Concrete Institute, *Building Code Requirements for Reinforced Concrete*, ACI Standard 318, Detroit: American Concrete Institute.


Chapter 4 Interface Complexity

4.1 Introduction

In the context of Axiomatic Design [18], information content refers to the level of technical complexity in a design decision. The design alternative with the minimum information content has the highest probability of success and, therefore, is the most optimal mapping between functional requirements and available resources. Resources is a broad term that encompasses the diverse body of knowledge related to the creation of a product. In the domain of constructed facilities, this knowledge includes the materials, components, and equipment that physically define and build a structure, the designer’s comprehension of the behavior of structural concepts, and the contractor’s understanding of the processes and methods necessary for construction.

For applications within a single domain, such as mechanical design, past publications [18,19,20,21] have shown the Independence Axiom combined with Shannon’s [17] logarithmic definition of information content to be sufficient for evaluating the relative merit of uncoupled or quasi-coupled designs. Multi-disciplinary design, however, can introduce explicit and/or implicit couplings among functional requirements that are not easily quantifiable in terms of probabilistic expressions.

Explicit couplings occur when different disciplines make use of the same information, such as the expression of aesthetics through structural form and the merging of mechanical systems with structural elements in order to increase a building’s usable space. Implicit couplings are derived from the fact
that the design artifacts created by each discipline are ultimately integrated into a complete system. As a result of this integration, both physical and functional interfaces can occur among the design and construction elements.

Interface issues are an additional type of complexity because they often are a source point for problems that can beset the design, construction, and operation phases of a project's life-cycle, [22]. One measure of the impact of interface issues on civil design projects is the number of change orders generated during field construction. The Goal Progress Reporting System audit of the Naval Facilities Engineering Command for fiscal year 1987 reported change order costs totalling $146.3 million, which is equal to 5.1% of the total yearly construction expenditure, [4]. Berenato [4] also cites a change order rate in the civilian sector that averages about 5% of the total construction costs. Recognizing the importance of field coordination for resolving interface issues, owners are now investing in construction management services to oversee the construction and start-up of complex multi-disciplinary projects such as power plants and high-technology facilities.

The objective of this chapter is to present a design metric that measures the interface complexity associated with design and construction planning decisions. A rational measure of interface complexity aids in integrating design solutions so as to improve design quality in both the physical and process domains. In addition, the proposed interface measure provides an objective referent for comparing alternative solution concepts. This interface measure is termed the Interface Index.

Development of an analytical expression for the Interface Index borrows from graph theory [8,11] and research in the
area information-based metrics to support the design of software systems [3,6,7,10,12,14,23,24]. Similar to this author’s negative view of the influence of interface issues on the design and construction of constructed facilities, research on the complexity of software systems supports system architectures that can be characterized as clusters of modules with few inter-module connections. This modularity implies that software modules can be independently developed, modified, and corrected without critically affecting the other modules of a system, [1]. Graph theory provides a mathematical technique for quantifying how much the structure of a proposed product or process design deviates from an idealized, modular configuration.

The following section provides some background information concerning design metrics for software engineering. Sections 4.3 and 4.4 present the development and verification of the proposed Interface Index.

4.2 Information-based Software System Design Metrics

Couplings within system design and process plans must be resolved by information passing between the impacted agents. The notion of an Interface Index is proposed as a measure of design complexity associated with information passing. This definition of design complexity is consistent with the approach adopted by the developers of system design metrics for software engineering.

Alexander’s design text Notes on the Synthesis of Form [2] is cited by software researchers [14,24] as a first-source for recognizing the contribution of element couplings to the concept of design complexity. Originally directed toward the modern architectural community, Alexander’s work [2] outlines a program for design that can be seen to support the concepts
of modularity, information hiding, and data abstraction utilized in modern software environments such as structured [1] and object-oriented programming [5]. The major principle advanced by Alexander [2] is the fact that the component parts of any well-designed entity function in isolation from one another. This condition is equivalent to the Independence Axiom postulated by Suh and his co-workers [20,21] more than ten years later. Alexander refers to the interaction among the coupled elements of a design as an information transfer. This information transfer increases design complexity because it is difficult to synthesize and control variables that "exercise mutual constraint over one another’s states" [2].

Guided by this relationship between design complexity and functional inter-dependence, research on the complexity of software systems seeks to optimize the decomposition and partitioning of systems on the basis of data flow. However, the ability to reason effectively about the modularity or quality of a proposed system design requires a design metric that is sensitive to changes in system structure. Such a metric should measure interfaces and help to identify both the causes of and possible solutions to a design’s deficiencies, [10].

The literature contains many information-flow metrics for the design of software systems [3,6,7,10,12,14,23]. These measures are computed as objective functions of the quantifiable aspects of system structure, such as the ratio of inter-module links to the total number of links in the system [3] and the number of data calls from a module to other modules [7]. The validity of a proposed software design metric is typically demonstrated through statistical correlation with logic errors occurring in developmental software systems.
Similar to couplings between the modules of a software system, couplings among design elements and among construction activities are a set of factors that must be considered during design and construction planning, [9]. Thus, a valid metric is required that is sensitive to information passing during design and construction planning. The concept of an Interface Index is derived below.

4.3 Development of Interface Index

Figure 4-1 depicts the hierarchical decomposition of the design structure for a complex product or process. The overall system S is comprised of subsystems p and q, and the description of each of these subsystems, in turn, is obtained from the set of design variables (DV1,DV2,DV3,DV4). The solid lines correspond to an idealized, modular design structure that maintains the independence of each subsystem. Subsequent integration of the two subsystems into a complete system, however, introduces the inter-system couplings denoted by the dotted lines. As a result of these couplings, functional independence is compromised, and the design is termed complex.

In terms of information content, inter-system couplings increase the information content for a complex design versus that for a modular design structure. Thus, an amount of excess information can be identified when a complex system is decomposed into its component parts, [15,16,24]. The notion of excess information $\Delta I$ is demonstrated by the Venn diagrams in Figure 4-2.

When a system is composed of two independent subsystems p and q, the information content of the system is equal to the sum of the information measures for the two subsystems, and there is zero excess information $\Delta I$. 

149
FIGURE 4-1.  HIERARCHICAL STRUCTURE OF COMPLEX SYSTEM
$\Delta I = I(p) + I(q) - I(\text{SYSTEM})$

$\Delta I = I(q)$

$\Delta I = 0$

CONCEPT OF EXCESS INFORMATION $\Delta I$

FIGURE 42.
\[ I(\text{System}) = I(p) + I(q) \] (4-1)

where: \( p \cap q = \emptyset \)

\[ \Delta I = [I(p) + I(q)] - I(\text{System}) = 0 \] (4-2)

As the amount of overlap between subsystems \( p \) and \( q \) increases, the amount of joint information increases. Consequently, the sum of the individual information measures for each subsystem, \( I(p) + I(q) \), is greater than the information content of the total system, \( I(\text{System}) \), and \( \Delta I \) is non-zero and positive. This excess information represents the information content associated with interface issues. It is termed the Interface Index.

\[ I(\text{Interface}) = \Delta I = \text{Interface Index} \] (4-3)

Similar to the previously cited complexity metrics for software design, values for excess information \( \Delta I \) can be determined from the analysis of system structure. The concept of a system graph is a convenient visual tool for aiding in the analysis of physical systems, such as electrical networks, mechanical devices, and structural frames [8,11]. A system graph provides a schematic diagram of system components and interconnections. In addition, the application of graph-theoretic principles to a system graph presents a mathematical framework for system synthesis, analysis, and control [11].

By analogy, the design hierarchy established during design or construction planning can be viewed in terms of a system graph. A graph is defined as a set of vertices connected by arcs or edges, and each edge is associated with a pair of vertices, [8]. Operationally, a three-stage process is
needed to construct and analyze the system graph associated with a given system design.

In the first stage, vertices are used to outline the proposed solution in terms of its underlying subsystems and components. During the second stage, edges are inserted between vertices so as to indicate how the functional requirements of the proposed system are controlled by the design variables that describe its elements. Lastly, the basic theory of graphs is used to quantify how much the completed system graph deviates from a modular structure, and this deviation is a measure of the excess information $\Delta I$ shown in Figure 4-2.

Figure 4-3, for example, depicts a graph-theoretic interpretation of the design hierarchy shown in Figure 4-1. This system graph is defined by the set of vertices \(\{v_1, v_2, \ldots, v_7\}\) and the set of edges \(\{e_1, e_2, \ldots, e_8\}\). Through comparison with Figure 4-1, it can be seen that the subgraph consisting of the edge subset \(\{e_1, e_2, e_3, e_4, e_5, e_6\}\) and the included set of vertices \(\{v_1, v_2, \ldots, v_7\}\) corresponds to a modular design structure. In graph theory, this particular subgraph is called a spanning tree. By definition, a spanning tree of a graph $G$ is a subgraph that contains all vertices of $G$ and there is exactly one path between every pair of vertices, [8].

Edges $e_7$ and $e_8$ of Figure 4-3 provide additional paths or links between vertices $v_2$ and $v_3$, each additional link creates a number of circuits within the system graph. Traversing the subgraph \(\{v_2, e_7, v_6, e_5, v_3, e_2, v_1, e_1, v_2\}\), for example, is a circuit because the starting vertex $p$ can be reached without tracing an edge or a vertex more than once. Obviously, it is difficult to control the performance of a system that contains circuits because the subsystems are not
FIGURE 4-3. GRAPH-THEORETIC INTERPRETATION OF THE COMPLEX SYSTEM OF FIGURE 4-1
modular and there are multiple control paths for effecting changes.

Finding a spanning tree of a graph G that has circuits involves the sequential removal of edges until the last circuit is deleted, leaving a subgraph that contains all vertices of G, [8]. Although a graph can have multiple spanning trees, the number of edges that must be removed is a fundamental and invariant property of the graph. Thus, we can view the complexity of a coupled design in terms of its deviation from a spanning tree, and the excess information $\Delta I$ can be equated to the number of edges that must be removed so as to produce a spanning tree.

Specifically, the number of edges in a graph G that are not in a given spanning tree is called the nullity of G, [8]. If $v$ is the number of vertices and $e$ is the number of edges, the nullity of graph G is defined as [8]:

$$\text{nullity of } G = e - v + 1$$  \hspace{1cm} (4-4)

Equating Equations (4-3) and (4-4) yields an expression for Interface Index $\Delta I$:

$$\text{Interface Index, } \Delta I = e - v + 1 = \text{nullity}$$  \hspace{1cm} (4-5)

where $e$ and $v$ refer to the number of edges and vertices, respectively, in a graphical representation of the design structure.

For example, Figure 4-3 has 8 edges and 7 vertices, and its Interface Index is computed as follows:

$$\text{Interface Index, } \Delta I = 8 - 7 + 1 = 2 \text{ links}$$  \hspace{1cm} (4-6)
Equation (4-6) indicates that two edges must be deleted from the design structure in order to obtain a modular product or process.

4.4 Implementation Within Design Process

Since the performance of a system is derived from its subsystems, components, and the relationships among these elements, the process of removing edges from a design's system graph corresponds to redesign of the proposed product design or process plan. Edges cannot be deleted arbitrarily because they represent physical or logical phenomena. Consequently, an integrated design team is needed to identify and resolve interface issues effectively.

Historically, the U.S. construction industry tends to separate the individual design agents associated with the project phases of conceptual planning, design, procurement, and construction. The resulting decision-making structure is depicted in Figure 4-4, and it corresponds to a single-level, multi-goal system as defined by Mesarovic et al. [13]. This decentralized model is comprised of a group of specialized design agents, each with its own goal. The communication between the agents is informal, and many coordination decisions are resolved during field construction, resulting in delays, change orders, and cost overruns.

Coordination of the single-level, multi-goal system during a project's design phase relies on the development of a coalition-type strategy among two or more design agents, [13]. The success of the coalition is dependent upon designers who have sufficient experience to a) understand the interface issues, b) anticipate potential conflicts with other disciplines, and c) work with these other disciplines
FIGURE 4-4. FRAGMENTED DESIGN COORDINATION
to advance project goals. Consequently, it is not uncommon for an architectural firm to work with a preferred group of structural, mechanical, and electrical engineering firms. The weakness of this coalition-type approach is the fact that the development of future designers is heavily dependent upon some type of apprenticeship because it is otherwise difficult for senior designers to transmit their knowledge and experience to junior staff members. Although this strategy may serve the purposes of the individual design agents, it is argued that the fragmented design process perpetuates a reliance on ad hoc techniques and impedes the advancement of the industry [22].

The concept of a system graph for a product or process is convenient for visualizing interfaces, yet an equivalent matrix representation is more convenient for computer processing of design information, especially during the design of large-scale systems with many design agents, [8]. Therefore, a preferred approach is to calculate the Interface Index $\Delta I$ from the structure of the design matrix $[A]$ that is used to define the mapping between the vector of functional requirements $(FR)$ and the vector of design variables $(DV)$,

$$(FR) = [A] (DV) \quad (4-7)$$

It can be shown that the Interface Index $\Delta I$ can be determined by partitioning the design matrix with respect to the various modules of a proposed system.

Consider the following design equation which defines subsystems $p$ and $q$ as uncoupled functions of the design variables $DV1$ and $DV2$.

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{bmatrix} DV1 \\ DV2 \end{bmatrix} \quad (4-8)$$
In Equation (4-8), the off-diagonal terms A_{12} and A_{21} are zero. This indicates that subsystems \( p \) and \( q \) are modular, and the nullity of the associated graph is zero. Thus, the Interface Index \( \Delta I \) is also equal to zero by definition.

In the case of the quasi-coupled design described by Equation (4-9), \( A_{21} \) is a non-zero, off-diagonal term.

\[
\begin{pmatrix}
\{p\} \\
\{q\}
\end{pmatrix} =
\begin{bmatrix}
X & 0 \\
X & X
\end{bmatrix}
\begin{pmatrix}
\{DV1\} \\
\{DV2\}
\end{pmatrix} \tag{4-9}
\]

Consequently, \( DV1 \) is connected to both subsystems \( p \) and \( q \), which corresponds to a link within the performance graph of the design. Due to this link, the design's graph has a nullity of one, and the Interface Index \( \Delta I \) is defined to be 1 link for information passing.

For the coupled design defined by Equation (4-10), the nullity of the design's graph is 2, i.e., \( A_{12} \) and \( A_{21} \) are non-zero elements and each element is a link within the corresponding performance graph. The resulting Interface Index is equal to 2 links for information passing.

\[
\begin{pmatrix}
\{p\} \\
\{q\}
\end{pmatrix} =
\begin{bmatrix}
X & X \\
X & X
\end{bmatrix}
\begin{pmatrix}
\{DV1\} \\
\{DV2\}
\end{pmatrix} \tag{4-10}
\]
4.5 References


Chapter 5  Application of Performance-Based Design to the Design of a Parking Garage: A Case Study

5.1 Introduction

The objective of this chapter is to validate the proposed methodology for performance-based design of constructed facilities. Validation is established empirically through use of a case study. Treatment of the case study involves review of the design and construction planning decisions associated with the delivery of an actual building project. The selected project is the parking garage for the Baybank Systems office complex in Waltham, MA. Elevational views of the complex are shown in Figures 5-1a and 5-1b. It is a mixed-use facility with a four-story office building overlying a four-story, cast-in-place, reinforced concrete structure with post-tensioned slabs. The appeal of the parking garage is one of scale: it provides a concise laboratory for reasoning about the merit of design and construction planning decisions and for studying the coordination problems arising from integration of the contributions of various designers and subcontractors.

Since construction of the parking garage had just been completed at the start of my involvement, the process of verifying the concept of performance-based design consists of defining appropriate functional requirements and working forward from these requirements to demonstrate convergence with the existing design drawings and construction plans. In this context, convergence means that recursive application of the concepts of functional decomposition, design axioms, and zig-zagging between the functional, physical, and process domains results in a logical and robust mapping sequence from functional requirements (FRs) to design variables (DVs) to
FIGURE 5-1. BAYBANK SYSTEMS OFFICE COMPLEX
1075 MAIN ST., WALTHAM, MA
construction plans. Successful mapping demonstrates the validity of the proposed framework as a descriptive methodology or roadmap for the project delivery process.

The crux of the case study, however, is to substantiate the use of the Independence Axiom [34], Information Axiom [34], and proposed Interface Index (see Chapter 4) as prescriptive criteria for recognizing good design. It is not necessary to demonstrate that these criteria were explicitly used in the design and construction of the parking garage, but it must be shown that they lead to solutions that satisfy multiple requirements with a relatively high probability of success.

Although the rationale for the various decisions made during the project delivery process may be readily apparent to the original agents, neither the completed physical structure nor the detailed package of design specifications and drawings provides a clear picture of the underlying logic, making it difficult to articulate the design process to others. If experienced designers truly seek solutions that are controllable [22,26] within certain bounds or tolerances, then the Independence Axiom should aid in focusing on multiple design requirements, extracting the pertinent pieces of information from the project, and identifying the design logic. Once the logic of the mapping between design domains is identified, the Information Axiom and the Interface Index are invoked as a means for quantifying design complexity with respect to both technical capability and interface issues. Specifically, the Information Axiom is used to quantify technical merit with regards to satisfying the stated requirements, and the Interface Index numerically defines the interface complexity due to couplings arising from the integration of subsystems into a total system.
Since the performance-based information necessary to evaluate and compare design alternatives is not formalized in the project documents, the evaluation of design merit per the Information Axiom is a knowledge-intensive task involving the gathering and synthesis of data from many sources. Therefore, the ability to define mathematically the ranges for solution alternatives in a non-textbook application demonstrates the feasibility of using the Information Axiom as a decision criterion for selecting an optimal solution. The validity of the proposed Interface Index as an analytical aid for reasoning about system integration is established by correlating areas of high interface complexity with actual difficulties encountered during field construction.

This chapter presents a systematic review and evaluation of the delivery process for the parking garage at the following levels of abstraction:

1. System design.
2. Subsystem design.
3. Component design.

System design is concerned with identifying concept solutions for the temporary leaving of automobiles, selecting the best solution, and developing a conceptual sketch. The conceptual sketch is an abstract line drawing or functional representation of the garage concept. A functional representation indicates how the solution concept is to accommodate user needs for accessing and storing vehicles. In addition, the system design phase expands the definition of the garage concept by identifying the physical subsystems necessary to satisfy the additional requirements associated with converting the conceptual sketch into a buildable and usable facility. These additional requirements consist of objective, regulatory criteria pertaining to structural
integrity and fire safety, as well as subjective criteria associated with aesthetic image and personal/vehicle security.

At the subsystem level, each subsystem is treated as an independent system with a unique set of functional requirements that must be satisfied. Once the appropriate mapping between FRs and DVs is established for each subsystem, the individual design matrices are assembled into a global matrix for identification of interface issues. Since the output of subsystem design superposes physical artifacts onto the abstract functional layout, construction planning is also introduced by mapping the subsystem design variables to construction systems or process variables.

For example, the subsystem design established for structural performance must satisfy functional requirements concerning durability, maintainability, reliability under applied load, and constructibility. The mapping from the functional domain to the physical domain is used to reason about how well the specified design variables satisfy durability, maintainability, and structural integrity under vertical and lateral loads. The mapping in the physical domain is also used to identify function-related interface issues with any of the other subsystems. The design variables are then mapped to construction systems in the process domain. Process mapping provides a context for reasoning about constructibility issues, such as repetition, modularity, standardization, and coupling among construction operations.

The component design stage transforms each subsystem into definitive construction elements, including detailed construction procedures. Consequently, the component descriptions establish much of the criteria necessary to make the design specification concrete and to develop detailed
drawings. Although there is an overall uniqueness to this parking garage project, many of the design and construction planning issues dealt with at the component level are generic issues involving engineering fundamentals (e.g., the design of specific structural elements) and basic construction operations (e.g., formwork construction and the placement of reinforcing steel). Thus, the design equations obtained from applying the concepts of performance-based design at the component level can be used repeatedly throughout the industry.

5.2 System Design

In this section, design of the parking garage at the system level is discussed. System characteristics define the layout of the facility in terms of its primary function: capacity for the temporary leaving of cars. The system description also identifies those subsystems necessary to support the performance of the parking garage in other areas, such as structural integrity, fire safety, and aesthetic properties.

5.2.1 Project Introduction

A New England-area developer is planning the construction of a new office building that will be sited on the outskirts of an urban center. In addition to satisfying the developer’s usage requirements by providing space for offices, conference rooms, and computer facilities, local by-laws stipulate that the project must provide a certain amount of off-street parking capacity. Based on the amount of space planned for commercial operations, 900 to 1000 parking spaces are to be provided for employees and visitors. As a result, the architectural brief outlines a mixed-use complex where a four-story office building is erected atop an above-ground,
multi-level car park.

5.2.2 Parking layout design

The developer's overall need for 900 to 1000 parking spaces is expressed as a functional requirement (FR1) at the outset. This requirement is then mapped one-to-one with a concept solution or design variable (DV1) consisting of an open car park with sprinklers. The merit of this decision can be evaluated by comparing the predicted system ranges of the possible solution alternatives: an open car park or a public parking garage, [12]. By BOCA code [12] definition, an open car park is one in which at least 50% of the facility is open to the weather at each floor on at least two sides. These exposure conditions contribute to fire safety by providing natural ventilation and reducing the potential for structurally-damaging heat buildup. Car parks offering more enclosure are classified as public parking garages and require alternative means for ventilation.

Figures 5-2 and 5-3 present probability distributions for the capacity of various size open car parks and public parking garages, respectively. These distributions are based on restrictions on the garage's permissible floor area and height of construction that are imposed by the available lot size and fire-safety limitations, [12]. Automatic sprinklers for fire suppression are also specified so as to maximize the permissible story height of the combined parking garage/office complex per building code specifications, [12]. An allowance of 200 to 400 square feet [36] per parking stall is assumed. Figure 5-2 confirms that a multi-story, open car park with sprinklers has the highest probability of providing sufficient floor space for parking 900 to 1000 cars.
FIGURE 5-2. RELATIONSHIP BETWEEN DESIGN RANGE AND PARKING CAPACITY OF VARIOUS MULTI-STORY OPEN CAR PARKS WITH AUTOMATIC SPRINKLERS
FIGURE 5-3. RELATIONSHIP BETWEEN DESIGN RANGE AND PARKING CAPACITY OF VARIOUS MULTI-STORY PUBLIC CAR PARKS WITH AUTOMATIC SPRINKLERS
Since the concept solution is not sufficient for implementation, the design process must zig-zag back into the functional domain. The original requirement for 900 to 1000 parking spaces is decomposed into serviceability requirements. The corresponding design variables describe the functional design of the parking garage. Functional design refers to the facility's operating characteristics, such as traffic flow patterns, means of egress, and layout dimensions for parking stalls and driving corridors, [13,17,25,38,39]. The resulting hierarchical mapping between the functional and physical domains is shown in Figure 5-4. The specified functional layout consists of a four-story open car park with a staggered floor configuration and two entries/exits. Floor-to-floor access is provided by a spiral of sloped floors that accommodate two-way traffic flow and parking. Since the driving corridors are designed for two-way traffic flow, parking is directed at a 90-degree angle to the traffic flow to enable stall access from either direction.

The following criteria can be used to evaluate the suitability of the parking garage's functional design, [13]:

1. Traffic flow capacity at peak hours.
2. Parking layout efficiency.

Traffic flow capacity measures the volume of cars that the car park's layout can accommodate during peak hours of operation without excessive amounts of travel time lost waiting to enter/exit the facility and circulating to/from parking spaces. Within certain tolerances, the flow capacity should be equal to the facility's static capacity, i.e., the total number of parking spaces provided. Typically, the flow capacity must permit filling or emptying of the car park's total static capacity, i.e. 900 to 1000 cars, within one-half
FIGURE 5.4. HIERARCHICAL MAPPING BETWEEN FUNCTIONAL AND PHYSICAL DOMAINS FOR FUNCTIONAL DESIGN OF PARKING FACILITY
hour, [13]. The efficiency of the parking layout refers to the average number of square feet per space. It is computed as the ratio of total garage floor area to the total number of parking spaces provided. Under 350 square feet per space is a desirable design range, but 350 to 400 square feet per space is often acceptable, [38].

Detailed analysis of the car park's traffic flow capacity is presented in Appendix B to this thesis. The resulting system capacity is approximated in Figure 5-5 as a uniform probability distribution with a lower limit of about 720 cars and an upper limit of about 1320 cars. Thus, the characteristic system range is about 600 cars. Figure 5-5 also indicates the required design capacity range of 900 to 1000 cars, and the design objective is to ensure that a significant percentage of the system capacity is bounded by the required design range. For a uniform distribution, the probability of success is simply given by the ratio, common range/system range, where common range refers to the amount of overlap between the desired capacity and the system capacity. In this case, the desired capacity range is wholly bounded by the characteristic system range. The common range is equal to 100 cars. Thus, the corresponding probability of success is 100/600, or 1/6, and the information content is given by:

$$ I = \log_2(6) = 2.58 \text{ bits} \quad (5-1) $$

Equation (5-1) indicates that there is not an exact match between the desired static capacity and the capacity derived from evaluating the functional layout with respect to traffic flow considerations. However, much of the variation in the calculated capacity reflects the effects of estimating values for input to the governing mathematical model. Review of the graphical representation shown in Figure 5-5 also indicates
FIGURE 5-5. RELATIONSHIP BETWEEN DESIRED CAPACITY AND PREDICTED SYSTEM RANGE
that the probability of undercapacity is less than that for overcapacity. Thus, the specified functional layout is judged to perform reasonably well with respect to traffic flow considerations.

One approach to quantifying efficiency is to use a scale of design satisfaction as shown in Figure 5-6. The graph in this figure assumes that the designer is 100% satisfied if the average area per space is less than 350 square feet, and design satisfaction decreases linearly from 100% to 0% if the area per space is in the range of 350 to 400 square feet. In addition, average parking spaces larger than 400 square feet are assumed to be unacceptable and are assigned a 0% probability of satisfaction. The actual garage layout specifies 950 parking spaces distributed over a total floor area of roughly 270,000 square feet. Since the efficiency is about 280 square feet per stall, the design satisfaction is 100% and the information content is 0 bits.

A schematic diagram of the proposed facility can be prepared on the basis of the completed functional design. The schematic is a line drawing indicating the outline of the car park, the location of parking stalls, and the established circulation routes. However, the schematic does not define the car park as a physical structure. Consequently, decomposition of the FRs defined at the lower level of Figure 5-4 is used to establish functional requirements leading to the design and construction of a physical structure.

Based on the taxonomy of performance requirements presented in Chapter 3, the additional functional requirements expand the scientific meaning of the project beyond the issue of serviceability to include concepts of reliability (FR= provide structural platform) and safety (FR= provide for fire safety; FR= provide for security of patrons and vehicles).
FIGURE 5-6.
CONCEPT OF DESIGN SATISFACTION FOR 
QUANTIFYING EFFICIENCY OF PARKING GARAGE
In addition, the symbolic meaning is defined by aesthetic requirements. Since the design progresses hierarchically, the mapping of the following FRs to design variables (DVs) is constrained by the established functional layout.

FR111= Provide fire safety.
FR112= Provide for the security of garage patrons and their motor vehicles.
FR113= Establish an aesthetic visual image.
FR114= Provide a structural platform to support multi-level parking.

Constraint= Maintain the given functional layout consisting of a four-story open car park with a staggered-floor configuration.

The above FRs are expressed in an indicial notation. The number of indices signifies the current level of abstraction, and the value assigned to each index uniquely defines the location of the requirement in the hierarchical tree. The functional requirements specified at each level of the hierarchy are numbered from left to right. Based on this convention, FRijk has three indices and is at the third level of abstraction. The value of the index i signifies the grandparent node, j identifies the parent node and k pinpoints the current leaf number. We see from Figure 5-7, for instance, that the requirement for a structural platform is the fourth leaf node sprouted from the functional requirement pertaining to traffic flow. In turn, the traffic flow requirement is the first leaf node obtained from the overall requirement to provide parking FR1. Therefore, the requirement for a structural platform is abbreviated by the term FR114. A similar notation will be used to reference the DVs and PVs.
FUNCTIONAL DOMAIN

FR1 = PROVIDE PARKING

FR11 = TRAFFIC FLOW
FR12 = ACCESS
FR13 = EFFICIENCY
FR14 = MANEUVER-ABILITY
FR15 = DRIVING AISLE

FR111 = FIRE SAFETY
FR112 = SECURITY
FR113 = AESTHETICS
FR114 = STRUCTURAL PLATFORM

FIGURE 5-7. HIERARCHICAL DECOMPOSITION IN FUNCTIONAL DOMAIN FOR DESIGN OF PARKING FACILITY AT SYSTEM LEVEL
5.2.3 Choice of DVs

A set of design variables that satisfy the requirements (FR111, FR112, FR113, FR114) is next identified from the design package. Since a comprehensive package of design information is available, care must be taken to ensure that the selected DVs correspond to the same level of abstraction as the posted FRs.

DV111 = Fire management system.
DV112 = Security system.
DV113 = Architectural details.
DV114 = Structural system.

The corresponding design matrix presented in Equation (5-2) identifies a one-to-one mapping between FRs and DVs.

\[
\begin{pmatrix}
FR111 \\
FR112 \\
FR113 \\
FR114
\end{pmatrix} =
\begin{bmatrix}
X & 0 & 0 & 0 \\
0 & X & 0 & 0 \\
0 & 0 & X & 0 \\
0 & 0 & 0 & X
\end{bmatrix}
\begin{pmatrix}
DV111 \\
DV112 \\
DV113 \\
DV114
\end{pmatrix} \tag{5-2}
\]

Equation (5-2) expresses the relationships between FRs and DVs in a Boolean manner: X signifies a strong functional dependence and 0 denotes a weak dependence or no dependence at all. The diagonal matrix indicates a one-to-one mapping between each FR and a unique DV; thus, the design satisfies the Independence Axiom, [34].

The right-hand side of Equation (5-2) lists the four subsystems that define the parking garage as a physical system. The need to define these four subsystems in further detail establishes the context for decomposition of the performance requirements FRijk. In addition, the diversity
of these subsystems sets the scope of the project as a multi-disciplinary effort, and the task of designing each subsystem can be used as a guide for organizing some of the design disciplines to staff the project team, e.g., architects, structural engineers, and fire safety engineers. Therefore, the lower level design matrices will be partitioned with respect to these four subsystems in order to compute Interface Indices.

5.3 Subsystem Design

The design process zig-zags back into the functional domain in order to generate specific, lower-level functional requirements for each of the four subsystems described by \{DV111, DV112, DV113, DV114\}. The resulting design hierarchy is shown in Figures 5-8 and 5-9. Figure 5-10 presents the related design equation. The elements of Figures 5-8, 5-9 and 5-10 are discussed below.

Fire safety. The local building code [12] imposes three requirements for an acceptable fire management system: suppress the fire, confine the movement of the fire, and provide adequate ventilation. For an open car park, the ventilation requirement is satisfied by definition. The design equation shown in Figure 5-10 indicates that the first two requirements are independently satisfied by an automatic sprinkler system and the use of fire barriers to impede the spread of fire from floor to floor.

Security. Personal and vehicular safety are imperative for successful garage operation, [25]. In addition to providing adequate visibility and perimeter barriers so as to reduce the potential for traffic accidents and personal injury, the security system also provides protection against unwanted intruders through a combination of lighting, posted guards,
Hierarchical Decomposition in Functional Domain for Design of Parking Facility at Subsystem Level

Figure 5.8.
FIGURE 5-9. HIERARCHICAL DECOMPOSITION IN PHYSICAL DOMAIN FOR DESIGN OF PARKING FACILITY AT SUBSYSTEM LEVEL
FIGURE 5-10. DESIGN EQUATION GOVERNING MAPPING BETWEEN FRs AND DVs AT SUBSYSTEM LEVEL
and access-control gates.

**Aesthetics.** The aesthetic requirements of unity and daring are drawn from Billington's framework [10] for the critical analysis of architectural design. Unity refers to the designer's efforts to combine the more pedestrian requirements of function and economy into a "harmonious" visual image, and the concept of daring refers to the adoption of a visual form that appears to challenge technology while satisfying the needs of its users [10].

The project architect opts to achieve unity of form by screening the car park in the red granite facade of the overlying office building. As a result of this screening, the garage structure emulates the richness of the project's focal element. A sense of daring is attained by offsetting the exterior column lines inward from the faces of the car park so as to cantilever the slab edges. Thus, the floor slabs appear to be unsupported, challenging convention.

**Structural platform.** Publications relating to the design of parking structures [5,13,16,25,36,37] indicate that premature structural deterioration is the major problem associated with structural performance. In addition to abrasive wear from vehicle traffic, parking structures built in northern climates face severe exposure to freeze-thaw cycles, extreme temperature ranges, and corrosive agents such as deicing salts and automotive fluids. These factors in combination with poor maintenance practices have resulted in effective service lives of about 10 to 20 years, rather than the estimated 50-year design life, [16,37]. Therefore, functional requirements for the structural platform address durability and maintenance concerns alongside gravity and lateral load resistance.
5.3.1 Performance Evaluation of Structural Platform

As a quantitative example, this subsection demonstrates the use of information content for evaluating the merit of the structural platform design with respect to the following requirements:

FR1141= Provide a durable structure capable of sustaining a 50-year service life.

FR1142= Provide a structure that is easy to maintain.

FR1143= Provide structural integrity against gravity loads.

FR1144= Provide structural integrity against lateral loads.

The design of the structural platform as a system is characterized by the following set of design variables:

DV1141= High-strength, concrete construction.
DV1142= Drainage system.
DV1143= Post-tensioned, flat-plate floor system.
DV1144= Rigid frame.
DV1145= Span length.

The associated design equation is given by Equation (5-3).

\[
\begin{align*}
\{FR1141\} &= \begin{bmatrix} X & 0 & 0 & 0 & 0 \end{bmatrix} \\
\{FR1142\} &= \begin{bmatrix} X & X & 0 & 0 & 0 \end{bmatrix} \\
\{FR1143\} &= \begin{bmatrix} X & 0 & X & 0 & X \end{bmatrix} \\
\{FR1144\} &= \begin{bmatrix} X & 0 & 0 & X & 0 \end{bmatrix} \\
\{DV1141\} &= \begin{bmatrix} \text{DV1141} \end{bmatrix} \\
\{DV1142\} &= \begin{bmatrix} \text{DV1142} \end{bmatrix} \\
\{DV1143\} &= \begin{bmatrix} \text{DV1143} \end{bmatrix} \\
\{DV1144\} &= \begin{bmatrix} \text{DV1144} \end{bmatrix} \\
\{DV1145\} &= \begin{bmatrix} \text{DV1145} \end{bmatrix}
\end{align*}
\]

Although there are more DVs than FRs, Equation (5-3) satisfies the Independence Axiom [34] since each FR can be uniquely controlled by a proper sequence of changes in the set of DVs. The design is classified as a redundant design.
because FR1143 can be satisfied by adjusting DV1143 and DV1145. Within certain tolerances, changes in the functional requirements for gravity load resistance can be satisfied by first specifying a characteristic span length DV1145 for the floor system and then using the proposed span length as input to the selection of an appropriate floor system.

In theory, the structure's ability to transfer and resist lateral load depends on combined diaphragm-action within the flat-plate floor system (DV1143) and lateral shear resistance of the rigid frame system (DV1144). In practice, gravity load effects are dominant for this size structure and the capacity for diaphragm-action is not as sensitive to variations in the floor slab system, especially since the inclusion of wind load permits a 25% reduction in load factor for dead and live loads, [6]. In addition, the use of a post-tensioned floor slab provides two separate mechanisms for resisting gravity and lateral load effects. Therefore, Equation (5-3) neglects the impact of coupling between the gravity load requirement (FR1143) and lateral load requirement (FR1144) through DV1143 and DV1144.

There are two methods for evaluating the performance of the specific solution concept generated by the structural engineer. The first approach is to consider simultaneously all requirements and design variables so as to compute the design's composite probability of success. This approach requires evaluation of the conditional probabilities associated with the non-zero, off-diagonal terms of the design matrix. Information theory [31] is then used to convert the joint probability expression into a measure of design complexity. For example, the total information for Equation (5-3) content is given by Equations (5-4a through 5-4i).
\[ I = I(\text{FR1141}) + I(\text{FR1142}) + I(\text{FR1143}) + I(\text{FR1144}) \]
\[ + I(\text{FR1142} | \text{DV1141}) + I(\text{FR1143} | \text{DV1141}) \]
\[ + I(\text{FR1144} | \text{DV1141}) + I(\text{FR1143} | \text{DV1145}) \]  \hspace{1cm} (5-4a)

\[ I(\text{FR1141}) = \log_2 \left( \frac{1}{P1} \right) \]  \hspace{1cm} (5-4b)
\[ I(\text{FR1142}) = \log_2 \left( \frac{1}{P2} \right) \]  \hspace{1cm} (5-4c)
\[ I(\text{FR1143}) = \log_2 \left( \frac{1}{P3} \right) \]  \hspace{1cm} (5-4d)
\[ I(\text{FR1144}) = \log_2 \left( \frac{1}{P4} \right) \]  \hspace{1cm} (5-4e)
\[ I(\text{FR1142} | \text{DV1141}) = \log_2 \left( \frac{P1}{P2} \right) \]  \hspace{1cm} (5-4f)
\[ I(\text{FR1143} | \text{DV1141}) = \log_2 \left( \frac{P1}{P3} \right) \]  \hspace{1cm} (5-4g)
\[ I(\text{FR1144} | \text{DV1141}) = \log_2 \left( \frac{P1}{P4} \right) \]  \hspace{1cm} (5-4h)
\[ I(\text{FR1143} | \text{DV1145}) = \log_2 \left( \frac{P5}{P3} \right) \]  \hspace{1cm} (5-4i)

where \( P_n \) is the probability of satisfying \( \text{FR114n} \) by varying \( \text{DV114n} \) and \( \left( \frac{P_n}{P_m} \right) \) is the conditional probability of satisfying \( \text{FR114n} \) by varying \( \text{DV114m} \).

The second approach for quantifying design merit uses the structure of the design matrix given in Equation (5-3) to compute the information content associated with each design variable in a sequential manner. Specifically, the optimality of high-strength concrete construction \( \text{DV1141} \) with respect to its probability of achieving a 50-year service life is first demonstrated. Based on this optimality condition, the merit of the solutions specified to simplify maintenance and resist the applied loads can be evaluated. The locations of the non-zero, off-diagonal elements of the design matrix indicate that confirmation of the construction material uncouples the maintenance and load resistance requirements. This lack of coupling allows a partitioning
of design tasks into parallel activities and reduces the complexity of the evaluative process.

The sequential approach to design evaluation will be used herein, and it is similar to the concept of dynamic programming which is a technique for structural optimization, [9,29,33]. Dynamic programming is a multi-stage approach to problem solving, and it is based on Bellman’s principle of optimality [9]: "An optimal policy (or a set of decisions) has the property that whatever the initial state and initial decision are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision." Thus, the serial nature of many problems in structural design can be exploited by transforming a problem that requires the joint optimization of n variables into a sequential suboptimization of n variables.

5.3.1.1 Evaluation of High-Strength Concrete Construction, DV1141

As discussed previously, open car parks in northern climates, such as New England, are subject to severe exposure conditions which compromise their effective service life. It can be argued, however, that the exposure conditions throughout the structure are not uniform, and differing severities can be attributed to the parking deck and the parking deck’s supporting elements. Columns and bearing walls are examples of possible supporting elements for the parking deck.

Intuitively, the parking deck faces the most severe exposure. In addition to freeze-thaw and thermal strain cycles produced by changes in ambient temperature, the deck is acted upon directly by moving vehicles, and its horizontal surface accommodates the deposition of snow, ice, and corrosive
agents. In contrast, vertically-orientated elements, such as columns and bearing walls, are primarily subject to ambient temperature changes that produce freeze-thaw cycles and thermal expansion and contraction.

The exposure conditions for the parking deck and supporting elements provide a rational basis for selection of optimal building materials. Table 5-1, for example, is extracted from Reference 27 and provides order of magnitude classifications for the service life of concrete and structural steel as a function of exposure condition. Based on the data presented in Table 5-1, the following three combinations of building materials are selected for consideration.

1. Both the parking deck and its supporting elements to be constructed from high strength reinforced concrete.

2. Parking deck to be constructed of high strength reinforced concrete. Supporting elements to be constructed from ordinary strength concrete.


Information measures corresponding to the probability of achieving a 50-year service life are needed to identify the optimal solution from among the above set of alternatives. In this case, the probability that a particular design alternative achieves a 50-year service life is given by the joint probability of its parking deck and support elements lasting 50 years, i.e.,

\[
\text{Probability} = P(50 \text{ yrs.} \mid \text{deck, supports}) \quad (5-5)
\]

Assuming that the probable service life values for the components are independent yields the following
<table>
<thead>
<tr>
<th>Material</th>
<th>Very Severe Exposure</th>
<th>Severe Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Strength Concrete</td>
<td>10 to 100</td>
<td>100 to 1000</td>
</tr>
<tr>
<td>Ordinary Strength Concrete</td>
<td>1 to 100</td>
<td>50 to 500</td>
</tr>
<tr>
<td>Structural Steel</td>
<td>1 to 10</td>
<td>10 to 100</td>
</tr>
</tbody>
</table>
simplification:

\[
P(50 \text{ yrs.} \mid \text{deck}) \times P(50 \text{ yrs.} \mid \text{supports})
\] (5-6)

and

\[
I = \log_2 \left( \frac{1}{P(50 \text{ yrs.} \mid \text{deck}) \times P(50 \text{ yrs.} \mid \text{supports})} \right)
\] (5-7)

Computation of information measures for each of the three alternative solutions requires transformation of the service life data presented in Table 5-1 into probabilistic expressions as shown in Figures 5-11 and 5-12. The development of these density functions is based on the following set of approximations.

1. Service life projections in Table 5-1 are considered to reflect the joint probability of \( n \) degradation modes. Log-normal distributions with parameters \( \mu_y \) and \( \sigma_y \) are used to represent service life as a continuous random variable, reflecting the product of a number of probability distributions, [35].

2. Parameters \( \mu_y \) and \( \sigma_y \) refer to the mean and standard deviation, respectively, of the random variable \( Y = \ln(\text{service life}) \)
   which is assumed to have a normal distribution.

3. For each material and exposure condition,
   \[
   \begin{align*}
   \mu_y &= 0.5 \times (\ln(t_0) + \ln(t_1)) \quad \text{(5-8a)}
   
   \sigma_y &= 2 \times (\ln(t_1) - \mu_y) \quad \text{(5-8b)}
   \end{align*}
   \]
   where \( t_0 \) and \( t_1 \) are equal to the lower and upper bound values of the service life ranges listed in Table 5-1. 

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FIGURE 5-11. PROBABILITY DISTRIBUTIONS FOR SERVICE LIFE OF BUILDING MATERIALS SUBJECTED TO VERY SEVERE EXPOSURE CONDITIONS
FIGURE 5-12. PROBABILITY DISTRIBUTIONS FOR SERVICE LIFE OF BUILDING MATERIALS SUBJECTED TO SEVERE EXPOSURE CONDITIONS
Information measures derived from application of Equation (5-7) to the probability density functions shown in Figures 5-11 and 5-12 are summarized in Table 5-2. Option 1, which consists of high-strength concrete construction throughout the structure, has the minimum information content and, therefore, is the optimal material choice. This confirms the fidelity of the selected building material.

5.3.1.2 Evaluation of Drainage System, DVI142

Poor maintenance practices accelerate structural deterioration resulting in either structural obsolescence or costly re-construction. Historically, the owners of parking structures have been reluctant to fund comprehensive maintenance programs despite the amount of their initial outlay for design and construction. In the New England area, for example, the initial investment is about $8,000 to $12,000 per car space [36], yet most maintenance efforts are limited to routine cleaning and snow removal.

Hill [16] argues that the reason for this paradox is that construction costs are financed through capital investment, while maintenance costs must be derived from income which is a separate account. As a result, parking structures are designed on the basis of lowest first cost without regard to life-cycle costs, and there is no incentive to advance design concepts that would have a higher construction cost, yet last longer without excessive maintenance costs, [16]. Consequently, a design solution is needed that complements routine maintenance activities and contributes to the long-term performance of the concrete structure.

ACI Committee 362 [5] cites water penetration through the parking deck as a major contributor to the deterioration of
<table>
<thead>
<tr>
<th>Design Option</th>
<th>Information Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.25 bits</td>
</tr>
<tr>
<td>2</td>
<td>2.28 bits</td>
</tr>
<tr>
<td>3</td>
<td>4.50 bits</td>
</tr>
</tbody>
</table>
concrete parking structures. Diffusion of water through the slab provides a mechanism for the corrosion of reinforcement, freeze-thaw structural damage, and deterioration of the concrete matrix, [4,5]. Therefore, the design of a concrete parking structure for maintainability must aid in the removal of water from all surfaces, and the use of a properly designed drainage system on each floor is the proposed solution. However, insufficient performance information is available to quantify the information content of this solution.

5.3.1.3 Evaluation of Post-Tensioned, Flat-plate Floor Slab System, DV1143

Table 5-3 lists concrete floor slab systems that are commonly used in parking structures. This list includes conventionally reinforced systems, prestressed systems, cast-in-place construction, and precast construction. The current format of FR1143, i.e.,

FR1143=Provide structural integrity against gravity loads,

is too vague to guide the rational selection of a floor slab system. The structural engineer must meet with the project architect (acting in the role of the client) so as to formalize the impact of the structural platform on the facility’s serviceability. For example, the architectural brief indicates that the parking garage is part of a mixed-use structure. In addition to the requirements presented in the brief, state and local building codes limit the overall height of the project to 85 feet. Thus, design of the parking structure is coupled to the design of the overlying office building: the permissible height of the car park is a function of the number of stories planned for the office building.
<table>
<thead>
<tr>
<th>System</th>
<th>Typical Span Length, ft.</th>
<th>Span-to-Depth Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cast-in-place Concrete</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Conventionally Reinforced</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>One-way slab and beam</td>
<td>15 to 40</td>
<td>L/20 to L/26 $^1$</td>
</tr>
<tr>
<td>Pan joist</td>
<td>20 to 60</td>
<td>L/20 to L/25</td>
</tr>
<tr>
<td>Two-way flat slab with drops</td>
<td>20 to 40</td>
<td>L/30 to L/40 $^2$</td>
</tr>
<tr>
<td>Two-way waffle slab</td>
<td>25 to 65</td>
<td>L/23 to L/35</td>
</tr>
<tr>
<td><strong>Post-tensioned</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>One-way slab and beam</td>
<td>30 to 80</td>
<td>L/20 to L/28 $^1$</td>
</tr>
<tr>
<td>Two-way flat plate</td>
<td>20 to 35</td>
<td>L/36 to L/44</td>
</tr>
<tr>
<td>Two-way flat slab with drops</td>
<td>35 to 45</td>
<td>L/40 to L/48 $^2$</td>
</tr>
<tr>
<td>Two-way waffle slab</td>
<td>35 to 70</td>
<td>L/24 to L/32</td>
</tr>
<tr>
<td><strong>Precast Concrete</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prestressed tees</td>
<td>40 to 120</td>
<td>L/20 to L/28</td>
</tr>
<tr>
<td>Prestressed hollow core units</td>
<td>10 to 40</td>
<td>L/25 to L/40</td>
</tr>
</tbody>
</table>

$^1$ Refers to depth of beam; total depth = depth of beam + overlying slab thickness

$^2$ Refers to flat slab thickness; total depth = slab thickness + depth of drop panel
Based on providing a four-story office building with an assumed floor-to-floor height of 12.5 feet, the resultant height allowance for the parking garage is defined by the following inequality:

\[ \text{Height} \leq 85 \text{ ft.} - (4 \text{ stories} \times 12.5 \text{ ft.}) = 35 \text{ ft.} \quad (5-9) \]

Since the designer is constrained to maintain the given parking layout design, the total garage height must be mapped to a four-story, staggered-floor configuration. Equation (5-9) limits the garage's floor-to-floor height to 8 ft.-9 in.

The floor-to-floor height of a parking garage is equal to the sum of the depth of the supporting floor system and the specified inter-floor allowance for vehicular clearance. For a maximum floor-to-floor height of 8 ft.-9 in. and a vehicular clearance of about eight feet (which is consistent with National Parking Association guidelines [25]), a nominal 9-inch floor depth is permitted. FR1143, therefore, can be restated as follows:

\[ \text{FR1143} = \text{Provide a gravity load system with a floor depth in the range of 8 to 10 inches}. \]

The candidate slab systems listed in Table 5-3 can now be evaluated as a function of their projected depth of construction. Table 5-3 includes typical span lengths and span-to-depth ratios for the cited floor systems, as extracted from References 24 and 30. Since the thickness of each floor system is dependent upon span length, determination of information measures for the various floor system alternatives requires transforming the tabulated span-to-depth ratios into a set of probability density functions for a given span length. Figures 5-13 and 5-14, for example, show density functions corresponding to a column
FIGURE 5-13. RELATIONSHIP BETWEEN DESIGN RANGE AND DEPTH OF CONSTRUCTION ASSOCIATED WITH CONVENTIONALLY REINFORCED CONCRETE FLOOR SLAB SYSTEMS (30-FT. MAXIMUM SPAN LENGTH)
FIGURE 5-14. RELATIONSHIP BETWEEN DESIGN RANGE AND DEPTH OF CONSTRUCTION ASSOCIATED WITH PRESTRESSED CONCRETE FLOOR SLAB SYSTEMS (30-FT. MAXIMUM SPAN LENGTH)
grid that includes a maximum span of 30 feet. The development of these density functions is outlined below and is similar to the previous treatment of service life data.

1. For each proposed column grid and associated maximum span length, a feasible set of floor slab systems are obtained from Table 5-3. Characteristic ranges for depth of construction are calculated for each element of the feasible set by application of the following equation:

\[
\text{Depth of Construction} = \frac{\text{Span Length} \times \text{Span-to-Depth Ratio}}{} \tag{5-10}
\]

2. The resulting range of slab depths is then mapped to an assumed normal probability distribution with parameters \( \mu \) and \( \sigma \). Parameters \( \mu \) and \( \sigma \) refer to the mean and standard deviation, respectively, and are estimated by the following set of equations.

\[
\begin{align*}
\mu &= 0.5 \times (d_0 + d_1) \\
\sigma &= 2 \times (d_1 - \mu)
\end{align*} \tag{5-11a,b}
\]

where \( d_0 \) and \( d_1 \) are equal to the lower and upper bound values of the slab depth ranges determined from Equation (5-10) and Table 5-3.

Information measures derived from integration of the probability density functions shown in Figures 5-13 and 5-14 are summarized in Table 5-4. The prestressed, flat-plate system has the minimum information content and is confirmed as the optimal floor system choice.

5.3.1.4 Evaluation of Rigid Frame System, DV1144

In addition to vertically-acting loads due to deadweight, usage, and snow, the car park must resist horizontally-acting
TABLE 5-4. INFORMATION MEASURES FOR SELECTION OF CONCRETE FLOOR SLAB SYSTEM
(30-FT. MAXIMUM SPAN LENGTH)

<table>
<thead>
<tr>
<th>Design Option</th>
<th>Information Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>* Conventionally Reinforced</td>
<td></td>
</tr>
<tr>
<td>Pan joist</td>
<td>*</td>
</tr>
<tr>
<td>Two-way flat slab with drops</td>
<td>*</td>
</tr>
<tr>
<td>Two-way waffle slab</td>
<td>5.47 bits</td>
</tr>
<tr>
<td>* Post-tensioned</td>
<td></td>
</tr>
<tr>
<td>Two-way flat plate</td>
<td>0.07 bits</td>
</tr>
<tr>
<td>Two-way flat slab with drops</td>
<td>*</td>
</tr>
<tr>
<td>Two-way waffle slab</td>
<td>*</td>
</tr>
</tbody>
</table>

* denotes $I=\log_2(1/0)$.  

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wind loads. Two types of structural systems for resisting the lateral loads are possible:

1. Rigid frame system, in which the lateral loads are transmitted through flat-plate slab and to supporting columns by diaphragm action. Structural stability is ensured by moment-resisting connections between the slab and columns.

2. Shear wall system, in which the floor slab system transmits all of the lateral load to a concrete wall or set of walls capable of resisting lateral shear. Pinned-joints provide sufficient connectivity between the slab and columns.

Because of the initial conditions imposed by the functional layout, the shear wall concept is the more difficult to integrate into the parking structure. Locating the shear walls at the structure's center of mass conflicts with the layout established for traffic flow and parking. Shear walls located along the periphery of the structure must be pierced with holes in order to avoid conflict with the ventilation requirements for fire safety. Holes in the shear wall are also required in order to avoid a conflict with the visibility requirements for security. As a result of these conflicts or interface issues, a rigid frame system, which offers open areas for ventilation, visibility, and traffic flow, is the optimal choice.

5.3.2 Constructibility Evaluations and Construction Planning

As discussed in Subsection 3.3.5, the intent of performing constructibility evaluations is to provide the designer with a feedback mechanism for advancing design alternatives that have a high probability of being produced economically. Subsection 3.3.5 defines the following complexity measures as relative referents for reasoning about constructibility:
1. Interface complexity associated with subsystem integration.

2. Technical complexity with respect to shop fabrication and field assembly activities.

Table 5-5 summarizes the calculated, information-based measures of constructibility. The analytical details associated with the tabulated performance measures are discussed below.

5.3.2.1 Interface Complexity

The concept of the Interface Index (see Chapter 4) is used to measure interface complexity. The Interface Index quantifies the number of functional and physical interfaces occurring among design elements and construction operations. Functional interfaces are identified through review of the mapping of subsystem requirements to design variables in the physical domain. During the design phase, inter-system couplings or interfaces occur when different design disciplines must make use of the same information, i.e., design variables are shared among two or more subsystems. Couplings between construction activities represent physical interfaces associated with the integration of subsystem elements into a complete system. Thus, satisfactory construction of one subsystem is contingent upon the successful completion of one or more other subsystems. Since each interface is a coordination point between designers or construction tradesmen, the Interface Index can be viewed as a measure of information transfer during task execution.

Figure 5-15, for example, is a re-working of the design equation governing subsystem design originally presented in Figure 5-10. The elements of the requirements vector on the left-hand side of Figure 5-10 are replaced in Figure 5-15 by
<table>
<thead>
<tr>
<th>Constructibility Measure</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Interface Index</strong></td>
<td></td>
</tr>
<tr>
<td>Design</td>
<td>2 links</td>
</tr>
<tr>
<td>Construction Planning</td>
<td>2 links</td>
</tr>
<tr>
<td><strong>Total Interface Complexity</strong></td>
<td>4 links</td>
</tr>
<tr>
<td><strong>Information Content</strong></td>
<td></td>
</tr>
<tr>
<td>Standardization</td>
<td>0.18 bits</td>
</tr>
<tr>
<td>Repetition</td>
<td>3.09 bits</td>
</tr>
<tr>
<td>Modularity</td>
<td>0.15 bits</td>
</tr>
<tr>
<td><strong>Total Technical Complexity</strong></td>
<td>3.42 bits</td>
</tr>
</tbody>
</table>
FIGURE 5-15.

SUBSYSTEM PARTITIONING OF DESIGN EQUATION FROM
FIGURE 5-10 TO CALCULATE INTERFACE INDEX ASSOCIATED WITH
DESIGN
the four characteristic subsystems: fire safety, security, aesthetics, and structural platform. The related design matrix is also partitioned to provide a visual aid for calculating the Interface Index. If no inter-system couplings are present, the partitioned design matrix \([A]\) can be represented by the following diagonal structure.

\[
\begin{bmatrix}
[A_1] & 0 & 0 & 0 \\
0 & [A_2] & 0 & 0 \\
0 & 0 & [A_3] & 0 \\
0 & 0 & 0 & [A_4]
\end{bmatrix}
\]

where \([A_i]\) is the submatrix for subsystem \(i\) that defines the mapping between the requirements vector \((FR)_i\) and the corresponding vector of design variables \((DV)_i\). The Interface Index reflects the amount of deviation from the above idealized, diagonal structure and is equal to the total number of non-zero terms appearing within the off-diagonal submatrices.

The partitioned design matrix of Figure 5-15 has a quasi-diagonal structure with the majority of the X-entries clustered in a narrow band about the main diagonal. Based on this partitioned structure, it is easy to identify the following two inter-system, functional couplings:

1. The ability of the design to satisfy the aesthetic requirement for unity of form is dependent upon both the red granite facade and the parapet, where the parapet is part of the security system.

2. The gravity load resistance of the structural platform is a function of both the prestressed flat-plate floor system and the cantilever slab condition specified for aesthetic purposes.

The above couplings produce an Interface Index equal to 2
links for information passing. They are explicit, functional links between subsystems and correspond to shared information between design disciplines. For example, the architect must be apprised of changes to the parapet design during development of design details for the red granite facade. Similarly, decisions to alter the cantilever conditions based on aesthetics must be reported to the structural engineer responsible for design of the prestressed slab.

Implicit, physical couplings indicative of potential interferences and mismatches during field construction and integration of the car park's four subsystems can be identified by mapping the design variables to construction operations in the process domain. This mapping is equivalent to the process of construction planning and can be articulated by the following matrix transformation:

\[
(DV) = [A] \{PV\}
\]

(5-12)

where: \(DV\)= vector of design variables.

\(PV\)= vector of process variables or construction operations.

\([A]\)= transformation or design matrix.

The resulting design equation for construction planning is presented in Figure 5-16. The set of design variables has been selectively pruned to focus only on the subset of variables that rely on field construction for implementation, i.e., the constructed systems and elements associated with providing fire safety, personal/vehicle security, aesthetic qualities, and a structural platform. The selected subset of design variables are mapped to the specialty contractors and construction methods actually used by the project.

Prior to addressing the issue of interface complexity, the
\[
\begin{align*}
\{ & \text{SPRINKLER SYSTEM} \\
& \text{LIGHTING SYSTEM} \\
& \text{PARAPET} \\
& \text{CANTILEVER SLAB} \\
& \text{RED GRANITE FACADE} \\
& \text{DRAINAGE} \\
& \text{POST-TENSIONED FLAT PLATE} \\
& \text{RIGID FRAME} \}
\end{align*}
\]

\[
\begin{align*}
& = \\
& \begin{bmatrix}
X & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & X & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & X & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & X & 0 & 0 & X & 0 \\
0 & 0 & X & 0 & X & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & X & X & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & X & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & X & X \\
\end{bmatrix}
\end{align*}
\]

\[
\{ & \text{PLUMBING CONSTRUCTION} \\
& \text{ELECTRICAL CONTRACTOR} \\
& \text{C-I-P UPTURNED BEAM CONSTR.} \\
& \text{C-I-P CANTILEVER CONSTRUCTION} \\
& \text{ARCHITECTURAL CONCRETE DRAIN CONSTR.} \\
& \text{C-I-P ELEVATED SLAB CONSTR.} \\
& \text{C-I-P COLUMN CONSTRUCTION} \}
\]

**FIGURE 5-16.** DESIGN EQUATION GOVERNING MAPPING BETWEEN DVS AND PVS AT SUBSYSTEM LEVEL
design matrix can be used to characterize the construction plan in regards to the Independence Axiom [34]. Since construction planning is just a special type of design problem, the construction plan should satisfy the principle of maintaining functional independence. From Figure 5-16, we can see that construction planning is governed by a lower triangular design matrix. The design is decoupled and, therefore, satisfies the Independence Axiom. Some of the design variables are quasi-coupled by their sequential dependence on concreting activities, while the specialty contractors responsible for the electrical and mechanical elements can be selected independent of all other requirements.

Again, the design matrix of Figure 5-16 can be partitioned so as to isolate sources of inter-system coupling during construction of the car park’s four sub-systems. The partitioned matrix is shown in Figure 5-17, and the associated Interface Index is equal to 2 links for information passing. In particular, it can be seen that the expression of aesthetic features through elements of the security and structural subsystems is the source of interface complexity. Consequently, execution of the activities necessary to construct these elements must be sensitive to the architect’s demands for visual quality.

The interface levels observed during subsystem design and construction planning appear to be quite tractable. However, it is important to note that inter-system couplings occurring early in the design process carry throughout the subsequent levels of decomposition. In fact, interface complexity increases non-proportionally with the depth of project detail because each design variable and process variable branches into a tree of subvariables. The component level of design detail, discussed in Section 5.4, illustrates how quickly
FIGURE 5-17. SUBSYSTEM PARTITIONING OF DESIGN EQUATION FROM FIGURE 5-16 TO CALCULATE INTERFACE INDEX ASSOCIATED WITH CONSTRUCTION
interface issues can become unmanageable.

5.3.2.2 Technical Complexity

Technical complexity with respect to shop fabrication and field assembly activities is a function of how well the construction process can exploit the concepts of standardization, repetition, and modularity (see Subsection 3.3.5). Design descriptions offering high levels of standardization, repetition, and modularity provide for ease of construction and minimize information content by promoting the use of widely accepted dimensions, tolerances, and techniques; learning-curve benefits and economies of scale; and a reduced number of assembly operations. The vector of construction activities or process variables (PV) listed on the right-hand side of Figure 5-16 provides a context for establishing information-theoretic measures of complexity.

For example, the decision to use cast-in-place concrete construction requires field erection of formwork to shape and support the fresh concrete until the concrete has gained sufficient strength to support itself. Although there are various formwork materials and equipment available for constructing flat-plate floor slab systems, such as handset wood construction and aluminum table forms [18,20,28], the 4’x8’ sheet of plywood is the industry-accepted, dimensional standard for surface forming [3,28]. Slab areas that deviate from this convention must be formed with the aid of filler pieces that contribute to material waste and increase the construction time required for cutting, fitting, and joining. Therefore, an information-based measure of standardization can be calculated as a function of the probability of covering or tiling the underside of all elevated floor slabs with standard 4’x8’ sheets of plywood.
Table 5-6 lists the various bay sizes specified for the car park's structural layout. For each bay size, values are entered for the unit area, number of occurrences, and the corresponding gross area, i.e., gross area = unit area times number of occurrences. The number of occurrences only pertain to elevated slabs because slabs formed on grade do not need supporting formwork. Table 5-6 also provides data concerning the area of each bay size that can be tiled by standard, 4'x8' sheets of plywood. From this analysis, the probability of standardization is 88%, and the associated information content is given by

\[ I(\text{Standard}) = \log_2 \left( \frac{1}{0.88} \right) = 0.18 \text{ bits} \quad (5-13) \]

Although the specified bay sizes are characterized by a high level of dimensional standardization, the amount of repetition in the slab layout is equally important because it can speed construction time by introducing learning-curve effects to task execution and by allowing for multiple uses of formwork, [1,7,8,18,23]. In terms of construction time, the repetitive use of unique forming patterns can have an advantage over the irregular use of standard dimensions because the time required for custom fabrication of the unique forming pattern can be amortized over a greater number of applications, [1,7,8]. If the floor slab layout has a large amount of variation, more effort is required for the tradesmen to interpret drawings, identify the appropriate forming strategy, and erect formwork. Thus, learning-curve advantages are difficult or impossible to realize.

Table 5-6 identifies the various bay sizes with their respective set of discrete and independent frequencies of occurrence $f_i$. The information measure for repetition is defined as:
<table>
<thead>
<tr>
<th>Bay Size</th>
<th>Unit Area</th>
<th>Standard Area</th>
<th>Quantity</th>
<th>Gross Area</th>
<th>Standard Area</th>
<th>Frequency of Occurrence</th>
<th>Repetition Complexity (bits)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32'x30'6&quot;</td>
<td>976</td>
<td>896</td>
<td>7</td>
<td>6832</td>
<td>6272</td>
<td>0.021</td>
<td>0.12</td>
</tr>
<tr>
<td>32'x25'6&quot;</td>
<td>816</td>
<td>768</td>
<td>55</td>
<td>44880</td>
<td>42240</td>
<td>0.163</td>
<td>0.43</td>
</tr>
<tr>
<td>32'x11'6&quot;</td>
<td>368</td>
<td>256</td>
<td>2</td>
<td>736</td>
<td>512</td>
<td>0.006</td>
<td>0.04</td>
</tr>
<tr>
<td>32'x9'11&quot;</td>
<td>317.4</td>
<td>256</td>
<td>7</td>
<td>2222</td>
<td>1792</td>
<td>0.021</td>
<td>0.12</td>
</tr>
<tr>
<td>28'6&quot;x30'6&quot;</td>
<td>869.3</td>
<td>672</td>
<td>18</td>
<td>15647</td>
<td>12096</td>
<td>0.053</td>
<td>0.23</td>
</tr>
<tr>
<td>28'6&quot;x25'6&quot;</td>
<td>726.8</td>
<td>672</td>
<td>10</td>
<td>79943</td>
<td>73920</td>
<td>0.326</td>
<td>0.53</td>
</tr>
<tr>
<td>28'6&quot;x11'6&quot;</td>
<td>327.8</td>
<td>224</td>
<td>7</td>
<td>2294</td>
<td>1568</td>
<td>0.021</td>
<td>0.12</td>
</tr>
<tr>
<td>28'6&quot;x10'10&quot;</td>
<td>308.7</td>
<td>224</td>
<td>1</td>
<td>307</td>
<td>224</td>
<td>0.003</td>
<td>0.02</td>
</tr>
<tr>
<td>28'6&quot;x9'11&quot;</td>
<td>282.7</td>
<td>224</td>
<td>18</td>
<td>5089</td>
<td>4032</td>
<td>0.053</td>
<td>0.23</td>
</tr>
<tr>
<td>14'3&quot;x25'6&quot;</td>
<td>363.4</td>
<td>288</td>
<td>25</td>
<td>9084</td>
<td>7200</td>
<td>0.074</td>
<td>0.28</td>
</tr>
<tr>
<td>12'x30'6&quot;</td>
<td>366</td>
<td>288</td>
<td>3</td>
<td>1098</td>
<td>864</td>
<td>0.009</td>
<td>0.06</td>
</tr>
<tr>
<td>12'x25'6&quot;</td>
<td>306</td>
<td>288</td>
<td>9</td>
<td>2754</td>
<td>2592</td>
<td>0.027</td>
<td>0.13</td>
</tr>
<tr>
<td>12'x11'6&quot;</td>
<td>138</td>
<td>96</td>
<td>1</td>
<td>138</td>
<td>96</td>
<td>0.003</td>
<td>0.02</td>
</tr>
<tr>
<td>12'x9'11&quot;</td>
<td>119</td>
<td>96</td>
<td>3</td>
<td>357</td>
<td>288</td>
<td>0.009</td>
<td>0.06</td>
</tr>
<tr>
<td>10'6&quot;x30'6&quot;</td>
<td>320.3</td>
<td>224</td>
<td>7</td>
<td>2242</td>
<td>1568</td>
<td>0.021</td>
<td>0.12</td>
</tr>
<tr>
<td>10'6&quot;x25'6&quot;</td>
<td>267.8</td>
<td>192</td>
<td>55</td>
<td>14726</td>
<td>10560</td>
<td>0.163</td>
<td>0.42</td>
</tr>
<tr>
<td>10'6&quot;x11'6&quot;</td>
<td>120.8</td>
<td>64</td>
<td>2</td>
<td>242</td>
<td>128</td>
<td>0.006</td>
<td>0.04</td>
</tr>
<tr>
<td>10'6&quot;x9'11&quot;</td>
<td>104.2</td>
<td>64</td>
<td>7</td>
<td>729</td>
<td>448</td>
<td>0.021</td>
<td>0.12</td>
</tr>
<tr>
<td>Totals</td>
<td>337</td>
<td>189320</td>
<td>166400</td>
<td>1.000</td>
<td>3.09</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
\[ I(\text{Repetition}) = \sum f_i \log_2 (1/f_i) \text{ bits} \quad (5-14) \]

Equation (5-14) expresses the complexity of the ensemble as the weighted sum of the complexity measures of the individual bay sizes. For bay size \( i \), the assigned weighting is equal to its frequency of occurrence \( f_i \) and its complexity measure is equal to \( \log_2(1/f_i) \). The format of Equation (5-14) is similar to that for entropy calculations in thermodynamics and statistical mechanics, [11,19]. It is sensitive to the amount of variation in the design specification because \( I(\text{Repetition}) \) is equal to zero if and only if all the \( f_i \) but one are zero. Application of Equation (5-14) to the frequency data entered in Table 5-6 reduces to the following information-based measure of complexity:

\[ I(\text{Repetition}) = 3.09 \text{ bits} \quad (5-15) \]

Lastly, the concept of modularity can be viewed as a meta-level approach to design repetition. It is a measure of whether the contractor may aggregate the formwork assemblies for individual bays into large panel, multi-bay systems that can be used extensively throughout the construction process. Formwork activities are greatly accelerated after the initial multi-bay system is created because most of the subsequent construction effort is devoted to moving and positioning the system, [1,2,7,18,23,28]. Review of the design drawings indicates that about 90% of the elevated slab area can be formed through use of three distinct modules. Therefore, the information-based measure of complexity is simply given by

\[ I(\text{Modularity}) = \log_2 (1/0.90) = 0.15 \text{ bits} \quad (5-16) \]
5.4 Component Design

The project delivery process zig-zags from construction planning in the process domain back into the functional domain for further decomposition of the functional requirements. The resulting requirements are shown in Figure 5-18, and they establish design criteria for substantiating the various subsystems. In fact, much of the criteria involves generic, routine design decisions for detailing the structural, sprinkler, and lighting systems and the parapet/facade. For example, requirements FR1143 and FR1144 pertaining to the garage’s structural integrity against gravity and lateral loads are decomposed into subrequirements calling for strength-based design of the flat-plate floor slab and rigid frame members, i.e., proportioning of structural members to ensure capacity against bending, shear, and axial stress effects.

The newly-created functional requirements presented in Figure 5-18 are mapped to a set of design variables, and these design variables are shown in Figure 5-19. Comparing the number of requirements posted in Figure 5-18 with the number of design variables listed in Figure 5-19 indicates that the design equation \( FR = [A](DV) \) is governed by a rectangular design matrix \([A]\) of dimension 35x38. Although the number of design variables (38) exceeds the number of requirements (35), the design equation does satisfy the Independence Axiom. The additional design variables are redundant, providing added parameters for controlling design response.

The vector of design variables \((DV)\) consists of the building blocks and elementary design properties comprising each subsystem. Thus, many of the design variables are terminal nodes for the decomposition process in the functional domain. This means that sufficient physical detail has been provided
FIGURE 5-18. HIERARCHICAL DECOMPOSITION IN FUNCTIONAL DOMAIN FOR DESIGN OF PARKING FACILITY AT COMPONENT LEVEL
**FIGURE 5-19. HIERARCHICAL DECOMPOSITION IN PHYSICAL DOMAIN FOR DESIGN OF PARKING FACILITY AT COMPONENT LEVEL**
so that subsystem performance can be clearly defined and a finer breakdown of FRs is not needed. Cross-sectional areas and steel reinforcing areas, for instance, are terminal nodes for designing the structural platform. As quantitative examples, Subsections 5.4.1 and 5.4.2 evaluate the capability of the structural platform in the areas of durability and constructibility, respectively.

Partitioning the design matrix with respect to the component designs provided for fire safety, security, aesthetics, and the structural platform identifies 28 pieces of shared information among these four subsystems. Thus, the Interface Index is equal to 28 links, and it has greatly expanded from 2 links at the previous level of design detail. Table 5-7 provides a breakdown of the interface measures occurring between the possible pairings of subsystems. We see from Table 5-7 that the 28 links of interface complexity in the physical domain are dominated by couplings between the structural platform and both the security and aesthetic subsystems. Specifically, detailed design of the flat-plate floor slab and rigid frame systems is dependent on the parapet’s cross-sectional dimensions and connectivity conditions generated during detailed design of the parapet as a protective vehicle barrier and as a visual screening. Thus, the eight requirements FR11431 through FR11435 and FR11441 through FR11443 for design of the structural platform are coupled to requirements FR11321 for aesthetics and FR11231 and FR11232 for security.

Construction process variables obtained from mapping the design variables into the process domain are shown in Figure 5-20. The dimension of the corresponding design matrix is 32x34, and the calculated Interface Index is equal to 265 links for information passing. This explosion in interface complexity as the design proceeds from the physical to the
<table>
<thead>
<tr>
<th>Subsystem Linkage</th>
<th>Interface Index</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design</strong></td>
<td></td>
</tr>
<tr>
<td>Fire Safety:Structural Platform</td>
<td>1 link</td>
</tr>
<tr>
<td>Security:Aesthetics</td>
<td>2 links</td>
</tr>
<tr>
<td>Security:Structural Platform</td>
<td>17 links</td>
</tr>
<tr>
<td>Aesthetics:Structural Platform</td>
<td><strong>8 links</strong></td>
</tr>
<tr>
<td><strong>Total Interface Complexity</strong></td>
<td><strong>28 links</strong></td>
</tr>
<tr>
<td><strong>Construction Planning</strong></td>
<td></td>
</tr>
<tr>
<td>Fire Safety:Security</td>
<td>13 links</td>
</tr>
<tr>
<td>Fire Safety:Aesthetics</td>
<td>0 links</td>
</tr>
<tr>
<td>Fire Safety:Structural Platform</td>
<td>56 links</td>
</tr>
<tr>
<td>Security:Aesthetics</td>
<td>29 links</td>
</tr>
<tr>
<td>Security:Structural Platform</td>
<td>111 links</td>
</tr>
<tr>
<td>Aesthetics:Structural Platform</td>
<td><strong>56 links</strong></td>
</tr>
<tr>
<td><strong>Total Interface Complexity</strong></td>
<td><strong>265 links</strong></td>
</tr>
</tbody>
</table>
FIGURE 5-20. HIERARCHICAL DECOMPOSITION IN CONSTRUCTION PROCESS
DOMAIN FOR DESIGN OF PARKING FACILITY AT COMPONENT LEVEL
process domain demonstrates the significance of integration issues at the component or detailed level of design. These couplings reflect coordination points for physically integrating the contributions of diverse construction tradesmen. Construction interfaces may be hidden from designers operating in the physical domain since they can only be determined by checking the nature of the mapping in the process domain. The growth in interface complexity also emphasizes the fact that the issue of constructibility must be addressed in unison with and concurrent with technical capability, even though the knowledge necessary to detail and construct each subsystem may exist in isolated domains. Table 5-7 also contains a breakdown of the interface measures associated with construction process planning. The trend toward large amounts of interfaces with the structural platform is confirmed by the topology of the facility. That is, the structural platform provides skeletal support for the fire safety, security, and aesthetic subsystems, as well as resistance to loads arising from usage and environmental effects. Support interfaces between the structural platform and the other subsystems vary in complexity from simple, exposed pipe hangers for supporting the sprinkler system (Interface Index = 8 links) to difficult, monolithic construction of the parapet along the edges of the flat-plate floor slab (Interface Index = 56 links). In the first case, the task of installing the galvanized pipe hangers on the underside of the floor slab follows construction of both the supporting columns and the slab formwork. For the latter case, the task of concrete placement for the parapet along the edges of the floor slabs also follows construction of both the supporting columns and the slab formwork, but it additionally must await complete construction of the flat-plate slabs, construction of parapet formwork, and the placement of rebar.
An additional bottleneck for field concreting activities is the design decision to use an architectural treatment of the parapet’s concrete as a means to simulate the texture, color, and cut stone effect of a red granite facade. Figure 5-21, for example, shows the design equation for the parapet/facade. Seven functional requirements are listed, and they refer to requirements FR11231 through FR11233 and FR11321 through FR11324 of Figure 5-18. The first three requirements refer to the design of the parapet as a vehicle barrier and establish the stability and strength of the parapet for resisting laterally-acting vehicular and wind loads. The remaining four requirements establish the parapet as an aesthetic element.

The corresponding design variables (DV11231 through DV11234 and DV11321 through DV11324) create a redundant design where concrete strength $f'_c$ is an additional variable for controlling the parapet’s lateral shear and bending resistances. In addition, partitioning the design matrix indicates that design of the parapet for resisting both lateral shear and bending is contingent upon the height specified to satisfy the screening requirement. Thus, there are two pieces of information overlap, and the Interface Index between the subsystems for security and aesthetics is equal to 2 links as indicated in Table 5-7.

Figure 5-22 presents the subsequent mapping of the parapet/facade design variables to construction tasks in the process domain. For simplicity, couplings with other subsystems have been removed in order to focus on the interface issues due to physical integration of the security and aesthetic issues. The Interface Index derived by partitioning the 8x9 design matrix is equal to 17 links. Based on the location of the coupling terms within the design matrix, it can be concluded that the use
**FIGURE 5-21.** DESIGN EQUATION GOVERNING MAPPING BETWEEN FRs AND DVs FOR COMPONENT DESIGN OF PARAPET/FACADE
FIGURE 5-22. DESIGN EQUATION GOVERNING MAPPING BETWEEN DVs AND PVs FOR CONSTRUCTING COMPONENTS OF PARAPET/FACADE
of a single element for the parapet/facade hinders concrete placement activities. This conclusion has been validated through discussion with the contractor’s Project Manager for Field Operations. Concreting of the parapet was severely delayed by the efforts required to produce an architectural concrete of high visual quality. A reduced rate of concrete placement was needed in order to produce a uniform color and acceptable surface quality. In addition, the use of horizontal rustication strips tended to trap aggregates, reducing localized quality of the mix.

5.4.1 Durability Evaluation of Structural Platform

Detailed design of the structural platform is characterized by the following set of generalized objectives:

1. Design of the floor slab system and rigid frame so as to satisfy code-based [6,12] reliability criteria with respect to dead loads, live loads, wind loads, and seismic loads.

2. Functional design of drainage system so as to reduce the potential for ponding of water.

3. Design and detailing of components so as to avoid possible modes of concrete degradation during course of 50-year service life.

The governing design philosophy for reliability of the structural members is an ultimate strength approach taking inelastic strains into account. Load and resistance factors are used to ensure adequate reliability against overloads or undercapacities. Design of the drainage system relies on sloping floors and design of the drains and piping to accommodate design storm runoff. Durability-based design involves developing adequate resistance to each possible mode of degradation.
Figure 5-23, for example, presents the design equation governing durability-based design of the concrete components. The left-hand side of the equation is a vector of the possible degradation modes for exposed concrete, and the resistance to each mode is treated as a functional requirement. The corresponding vector of design variables on the right-hand side of the equation contains parameters for controlling the intrinsic durability of the concrete material itself (e.g., water-to-cement ratio w/c, use of air-entraining agents, and use of silica fume additive) and for controlling the degradation of composite components (e.g., amount of clear concrete cover over reinforcing steel, use of epoxy-coated rebars, and the inclusion of expansion joints to alleviate the potential effects of restrained thermal expansion).

Reference 32 demonstrates the feasibility of using a probabilistic approach to predict durability performance of floor slabs with regards to attaining a desired service life. As a supplement to this earlier work, this subsection examines the probability of failure associated with chloride-initiated corrosion of the reinforcing steel in the concrete floor slab system. A mathematical model is used to calculate the probability of attaining the specified 50-year service life, and this probability is then converted to a measure of information content. The design equation presented in Figure 5-23 indicates that the following design variables are significant in determining the resistance of the concrete and reinforcing steel to the ingress of chloride ions from the use of de-icing salts:

1. Water-to-cement ratio, w/c.
2. Use of silica fume admixture.
3. Clear concrete cover over reinforcing steel.
4. Use of epoxy-coated reinforcing steel.
FIGURE 5-23. DESIGN EQUATION GOVERNING DURABILITY-BASED DESIGN OF CONCRETE SLAB
Specifically, each of the above parameters impact the effective diffusion coefficient for the transfer of chloride ions through the composite concrete/reinforcing steel system of components.

The probability density function shown in Figure 5-24 depicts the variation in concrete service life due to chloride-initiated corrosion of the reinforcing steel. This distribution is based on an approximate First-Order-Second-Moment [14,35] analysis of chloride diffusion. The details of this analysis, including the mathematical model governing diffusion of chloride ions, are provided in Appendix C to this thesis. According to the chloride diffusion model and the input data, the density function is normally distributed with a mean value \( \mu = 367 \) years and a standard deviation \( \sigma = 121 \) years. These stochastic properties yield a virtual 100\% probability of achieving the desired 50-year service life. The associated measure of technical complexity or information content is nearly 0 bits. Thus, the concrete mix design and the component details perform exceptionally well with respect to chloride-initiated corrosion of the reinforcing steel.

### 5.4.2 Constructibility Evaluation of Structural Platform

Similar to the treatment of the subsystem design detailed in Subsection 5.3.2, constructibility evaluations of the structural platform involve quantifying design complexity with regard to the degrees of standardization and repetition. Table 5-8 summarizes the resulting information-based complexity measures obtained from evaluation of the reinforcing steel for the flat-plate floor slabs (DV11441), formwork (DV11432) and reinforcing details (DV11442) for the reinforced concrete columns, and the shearheads (DV11434)
FIGURE 5-24. RELATIONSHIP BETWEEN 50-YEAR DESIGN SERVICE LIFE AND PREDICTED CONCRETE SERVICE LIFE
<table>
<thead>
<tr>
<th>Constructibility Measure</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interface Index</td>
<td></td>
</tr>
<tr>
<td>Design</td>
<td>28 links</td>
</tr>
<tr>
<td>Construction Planning</td>
<td>202 links</td>
</tr>
<tr>
<td>Total Interface Complexity</td>
<td>293 links</td>
</tr>
<tr>
<td>Information Content</td>
<td></td>
</tr>
<tr>
<td>1. Reinforcing Steel for Flat-Plate Slab</td>
<td></td>
</tr>
<tr>
<td>Bar Size Standardization</td>
<td>0.00 bits</td>
</tr>
<tr>
<td>Bar Length Standardization</td>
<td>2.93 bits</td>
</tr>
<tr>
<td>2. Column Formwork and Reinforcing Steel</td>
<td></td>
</tr>
<tr>
<td>Formwork Standardization</td>
<td>0.00 bits</td>
</tr>
<tr>
<td>Formwork Repetition</td>
<td>1.00 bits</td>
</tr>
<tr>
<td>Rebar Size Standardization</td>
<td>1.07 bits</td>
</tr>
<tr>
<td>Rebar Pattern Repetition</td>
<td></td>
</tr>
<tr>
<td>12&quot;x24&quot; column</td>
<td>0.99 bits</td>
</tr>
<tr>
<td>16&quot;x16&quot; column</td>
<td>0.65 bits</td>
</tr>
<tr>
<td>20&quot; dia. column</td>
<td>0.53 bits</td>
</tr>
<tr>
<td>3. Shearheads</td>
<td></td>
</tr>
<tr>
<td>Standardization</td>
<td>0.00 bits</td>
</tr>
<tr>
<td>Pattern Repetition</td>
<td></td>
</tr>
<tr>
<td>12&quot;x24&quot; column</td>
<td>0.00 bits</td>
</tr>
<tr>
<td>16&quot;x16&quot; column</td>
<td>0.00 bits</td>
</tr>
<tr>
<td>20&quot; dia. column</td>
<td>0.63 bits</td>
</tr>
<tr>
<td>Total Technical Complexity</td>
<td>7.80 bits</td>
</tr>
</tbody>
</table>
contributing to the shear resistance of the floor slabs in the vicinity of the supporting columns.

Since the constructibility evaluations involve distributed systems of discrete components, the complexity measures are given by:

\[ I = \sum f_i \log_2 \left( \frac{1}{f_i} \right) \text{ bits} \]  

(5-17)

where: \( f_i \) = frequency of occurrence of discrete element \( i \).

Equation (5-17) defines the total information content of the set of elements as the weighted sum of the complexity measures for each element. This distributed approach to calculating complexity is similar to the treatment of repetition in Subsection 5.3.2, Equation (5-14). Development of the tabulated data is discussed below.

5.4.2.1 Reinforcing Steel for Flat-plate Floor Slabs

Reinforcing steel is included in the post-tensioned floor slab system for resisting bending effects due to vertically-acting live loads and, to a lesser extent, laterally-acting wind loads. The relatively shallow cross-section of the floor slab is achieved by balancing the slab's deadweight through application of an internal system of prestressing forces. Since the slab also must gather and transmit vertically-acting live loads due to vehicle parking and snow, reinforcing steel is superposed near the top and bottom surfaces of the floor slab to provide bending resistance against lateral load effects. The reinforcing steel also must contribute to the flexural resistance of the entire framework against wind loads.
Degree of standardization of the reinforcing steel is calculated with respect to reinforcing bar size and bar length. Variations in bar size and/or bar length increase the level of site effort necessary for sorting the bundles of delivered bars and for ensuring proper placement. Review of the detailed drawings indicates that all bars for slab reinforcement are specified to be Standard ASTM #6 reinforcing bars. The size designation indicates the number of eighths of an inch included in the nominal diameter of the bars, e.g., a #6 reinforcing bar has a nominal diameter of 0.75 inches. Thus, standardization with regard to bar size has an information content of 0 bits because only one bar size is specified. Table 5-9 provides bar length data for the floor slabs, including frequencies of occurrence. The weighted sum of the individual complexity measures per Equation (5-17) is equal to 2.93 bits.

5.4.2.2 Column Formwork and Reinforcing Steel

Column formwork is used to support the freshly-placed concrete and to ensure that the concrete is of the correct height and cross-sectional dimensions. Standardization of column cross-sections reduces the time and materials required for formwork fabrication and assembly by enabling the use of prefabricated formwork or flexible formwork construction from a kit of standard parts. A Boolean scale of design satisfaction is used to quantify the standardization of column dimensions with respect to formwork construction, as shown in Figure 5-25. The graph in this figure indicates that a column dimension is either 100% or 0% satisfactory depending on conformance with a catalog of standard formwork dimensions. A 12-inch column, for instance, has a 100% probability of satisfaction, and the resulting information content is equal to 0 bits. On the other hand, an 11-inch
<table>
<thead>
<tr>
<th>Bar Length</th>
<th>Quantity</th>
<th>Frequency of Occurrence</th>
<th>Weighted Complexity (bits)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5'6&quot;</td>
<td>30</td>
<td>0.006</td>
<td>0.04</td>
</tr>
<tr>
<td>6'</td>
<td>78</td>
<td>0.015</td>
<td>0.09</td>
</tr>
<tr>
<td>7'</td>
<td>705</td>
<td>0.135</td>
<td>0.39</td>
</tr>
<tr>
<td>7'6&quot;</td>
<td>863</td>
<td>0.166</td>
<td>0.43</td>
</tr>
<tr>
<td>9'</td>
<td>1247</td>
<td>0.240</td>
<td>0.49</td>
</tr>
<tr>
<td>10'</td>
<td>541</td>
<td>0.104</td>
<td>0.34</td>
</tr>
<tr>
<td>10'6&quot;</td>
<td>126</td>
<td>0.024</td>
<td>0.13</td>
</tr>
<tr>
<td>11'</td>
<td>502</td>
<td>0.097</td>
<td>0.33</td>
</tr>
<tr>
<td>20'</td>
<td>528</td>
<td>0.102</td>
<td>0.34</td>
</tr>
<tr>
<td>22'</td>
<td>578</td>
<td>0.111</td>
<td>0.35</td>
</tr>
<tr>
<td>Totals</td>
<td>5198</td>
<td>1.000</td>
<td>2.93 bits</td>
</tr>
</tbody>
</table>
FIGURE 5-25.  CONCEPT OF DESIGN SATISFACTION FOR QUANTIFYING STANDARDIZATION OF COLUMN DIMENSIONS
column is a non-standard dimension and the probability of satisfaction is 0%. The associated value of infinity for information content is a measure of the amount of effort that must be expended, relative to the use of a standard column dimension, to produce formwork for an 11-inch column from raw materials.

The design drawings specify the use of the following column sizes:

1. 12"x24" rectangular.
2. 16"x16" square.
3. 20" diameter circular.

Figure 5-25 indicates that the probability of satisfaction for each of the above three column sizes is 100%. Therefore, the complexity of the column formwork with respect to standardization is given by 0 bits of information.

Repetition of the column sizes is indicative of the contractor's ability to re-use specific formwork configurations. The savings associated with a high-level of standardization can be lost on a project where the dimensions of each column are unique since the associated formwork is a one-time application [1,8,15,23] and there is great potential for errors during interpretation of the drawings by construction tradesmen [7]. The three column sizes specified for the garage project are characterized by the following frequencies of occurrence, \( f_i \).

1. 12"x24" rectangular: \( f_i = 0.75 \).
2. 16"x16" square: \( f_i = 0.05 \).
3. 20" diameter circular: \( f_i = 0.20 \).

Substitution of the above frequencies of occurrence into
Equation (5-17) yields an information content of about 1 bit. Thus, on average, formwork erection involves a decision between two equally probable selections, i.e., \( \log_2(2) = 1 \) bit.

Similar to the treatment of slab reinforcing steel in Subsection 5.4.2.1 above, standardization of the reinforcing steel for the concrete columns is calculated with respect to the variation in bar size and bar length. Column details for longitudinal reinforcing makes use of the following bar sizes with their associated frequencies of occurrence.

1. #8 bars: \( f_i = 0.26 \).
2. #9 bars: \( f_i = 0.0076 \).
3. #10 bars: \( f_i = 0.031 \).
4. #11 bars: \( f_i = 0.70 \).

The resulting complexity measure per Equation (5-17) is equal to 1.07 bits of information. Standardization of the column reinforcing steel with respect to bar length has a complexity measure of 0 bits because all inter-story heights are equal and, therefore, only one bar length is required. Thus, total complexity with respect to bar standardization is equal to 1.07 bits as entered in Table 5-8.

Table 5-8 includes information-based complexity measures associated with the degree of repetition of the reinforcing configurations or patterns. Information measures are given as a function of column size. For each column size, design details indicate two bar patterns for placement of reinforcing steel. A frequency of occurrence can be calculated for each option by treating each column size as a separate ensemble. Thus, the information measures listed in Table 5-8 for pattern repetition reflect application of Equation (5-17) to the set of possible rebar patterns for
each column size.

5.4.2.3 Shearheads

Shearheads constitute a local reinforcing system that enables the transfer of large, concentrated shear forces from the floor slab to the supporting columns. Project drawings indicate they are fabricated from 1/4-inch steel bar stock and standard 1/2-inch diameter headed studs. All shearheads are fabricated to conform with one type of configuration. This standardization minimizes the effort required to sort and handle the bundles of shearheads delivered to the site. Therefore, the complexity of the shearhead design with regard to standardization is equal to 0 bits of information, i.e., \( I = \log_2 (1) = 0 \) bits.

However, shearhead installation details vary with respect to column shape and column location. Since shearheads are to be distributed about the perimeter of the column section, placement patterns are necessarily dependent upon whether the column is located in the interior, along the edge, or at corner of the slab. Therefore, an ensemble of placement patterns can be identified for each column shape, and a frequency of occurrence \( f_i \) can be established for each element of the ensemble. The resulting complexity values shown in Table 5-8 are based on application of Equation (5-17) to the variation in placement patterns for each column shape. Since the 12"x24" rectangular columns are restricted to the interior of the facility and the 16"x16" square columns only occur along the borders of the layout, they have one characteristic placement pattern for shearhead installation, and evaluation of Equation (5-17) simplifies to zero bits of information. Twenty-inch diameter circular columns are specified for the interior and along the borders
of the facility layout with frequencies of occurrence of 0.84 and 0.16, respectively. Thus, their associated complexity is 0.63 bits of information.

5.5 Conclusions

Use of the proposed methodology for performance-based design has been demonstrated through application to the project delivery process for an existing parking structure. This application provides a comprehensive problem for studying the performance of the methodology as both a descriptive and prescriptive framework for design. This chapter provides four or more reasons for advancing the methodology as a valid framework for performance-based design.

Firstly, the use of the methodology as a descriptive framework for design has been confirmed. Successive application of the concepts of functional decomposition, design axioms, and zig-zagging between the functional, physical, and process domains has produced an explicit and logical mapping sequence from functional requirements to design variables to construction process variables. Thus, the concept of the design process as a black-box activity [21] has been refuted and externalized by the following, generalized matrix transformations:

1. \((FR) = [A1](DV)\)
2. \((DV) = [A2](PV)\)

Secondly, use of the Independence Axiom [34] for evaluating solution alternatives has been further substantiated. The case study has demonstrated that the diverse body of design variables and construction process variables generated by the responsible architects, engineers, construction contractors and subcontractors can be represented as design equations
satisfying the Independence Axiom [34]. Thus, the system-theoretic concepts of controllability and observability [22, 26] appear applicable within the domain of constructed facilities.

Thirdly, use of information content to evaluate the fidelity of the facility’s structural design indicates that the Information Axiom [34] can identify an optimal solution from a set of alternatives. In addition, the feasibility of basing design decisions on mathematical expressions of system capability has been demonstrated through application to an actual facility and not a student example.

Lastly, the concept of an Interface Index (see Chapter 4) as a numerical measure of inter-system coupling has been demonstrated. Its validity as a design aid for reasoning about ease of construction has been proven through correlation of areas of high interface complexity with actual difficulties encountered during field construction. For instance, the projected interface complexity of the parapet with regard to its connection with the floor slabs and its function as both an aesthetic element and a vehicle barrier has been confirmed through discussion with the contractor’s Project Manager for field construction.

The complexity of the project is dominated by the contribution of interface complexity at the level of component design and construction. This observation indicates that the individual designers perform better with respect to technical merit than with respect to system integration. That is, design decisions involving performance issues such as garage serviceability, structural platform, durability, and the degrees of standardization, repetition, and modularity typically have low information measures. The project’s interface complexity indicates that a considerable
volume of messages must be passed to coordinate design and construction activities. Thus, the next challenge for practicing designers appears to be the development of a strategy for reducing interface complexity.
5.6 References


4. ACI Committee 201, "Guide to Durable Concrete," ACI Committee Report 201, Detroit: American Concrete Institute.


6. American Concrete Institute, Building Code Requirements for Reinforced Concrete, ACI Standard 318, Detroit: American Concrete Institute.


Chapter 6 Targets for Innovation

6.1 Introduction

As elements of a prescriptive methodology for design, the concepts of the Independence Axiom [8], Information Axiom [8], and Interface Index (see Chapter 4) provide rational criteria for evaluating solution alternatives and selecting the optimal solution. They make explicit the relative shortcomings or merits of solution concepts. The emergence of a capability to at least evaluate on a relative basis the suitability of design alternatives with regard to functional requirements better enables practicing designers to identify specific weaknesses in their solutions. If established engineering systems are insufficient for satisfying the functional requirements, either the original requirements must be revised or innovative solutions must be created and evaluated. Thus, the design axioms [8] and the Interface Index also provide a framework for identifying targets for innovation.

Specifically, the following targets for product and process innovations can be identified:

1. Reduced intra-system coupling.
2. Reduced inter-system coupling.
3. Improved performance with new technology.

Intra-system coupling refers to solution concepts that do not satisfy the Independence Axiom. The term "intra-system" is used because the project delivery process is fragmented among a collection of design and construction experts working in isolated knowledge domains. Consequently, adoption of the Independence Axiom ensures that the subsystem and detailed component designs
developed within each domain are controllable with regard to their respective sets of requirements.

Inter-system coupling addresses the interfaces that arise when the distributed subsystems and components are integrated into a total system. A project's level of inter-system complexity, as quantified by the Interface Index, offers a reference value for reasoning about the amount of coupling associated with the performance of the system in the physical domain and the coordination of construction activities in the process domain. It reinforces application of the Independence Axiom across the complete system.

Lastly, representing the system range of established solution alternatives as probability distributions provides a visual aid for identifying gaps, overlaps, and capability limits for current technology. Technology gaps and limits are areas of opportunity for developing and advancing new technology, such as building systems, engineered materials, and automated construction equipment and techniques. New technology may also be needed to implement innovative solutions that are created to reduce intra-system and/or inter-system coupling.

The objective of this chapter is to consider the above three targets for innovation in the context of the parking garage case study examined in Chapter 5. Sections 6.2 and 6.3 provide examples indicative of the concepts of intra-system coupling and inter-system coupling, respectively. Each example is extracted from the parking garage case study, and its shortcomings are discussed. In addition, alternative solution concepts are proposed so as to achieve the desired target for good design, i.e., reduced intra-system coupling or reduced inter-system coupling.
The technology necessary to realize the newly proposed alternatives is then discussed in Section 6.4.

6.2 Reduced Intra-System Coupling

Figures 6-1 and 6-2 show the product and process design equations \((FR) = [A1](DV)\) and \((DV) = [A2](PV)\) that describe a portion of the component design process for the parking garage's structural platform. Figure 6-1 presents the mapping between the functional requirements for vertical and lateral load resistance and the corresponding design variables. Since the non-zero entries of the design matrix are configured in a lower triangular pattern, the design is decoupled and satisfies the Independence Axiom [8].

The design equation shown in Figure 6-2 defines the subsequent mapping of the design variables to construction process variables for implementation. The governing design matrix does not satisfy the Independence Axiom because the plan of activities for constructing the post-tensioned, flat-plate floor slab couples the installation of the post-tensioning system, bar reinforcement, and banded tendon system. Since scheduling logic dictates that two or more mutually-dependent activities cannot be started simultaneously [10], on-site resolution of this coupling condition required replacing the three activities by an iterative sequence of sub-activities. Execution of the sub-activities was then coordinated by continuous information exchange among the responsible tradesmen. This need for continuous information exchange increased the complexity of each task by adding to the amount of information that had to be processed in order to ensure proper placement of the post-tensioning system, bar reinforcement, and banded tendon system. Therefore, the
FIGURE 6-1. DESIGN EQUATION GOVERNING MAPPING OF FRs TO DVs FOR COMPONENT DESIGN OF STRUCTURAL PLATFORM
FIGURE 6-2. DESIGN EQUATION GOVERNING MAPPING OF DVs TO PVs FOR CONSTRUCTING COMPONENTS OF STRUCTURAL PLATFORM
floor slab system for the structural platform is a target for redesign so as to reduce intra-system coupling in the process domain.

Review of the analysis provided in Subsection 5.3.1 indicates that the post-tensioned, flat-plate floor slab system offers the optimal system range with regard to the requirement FR1143 for gravity load resistance, which is stated as follows:

FR1143= Provide gravity load system with a floor depth in the range of 8 to 10 inches.

The advantage of prestressed concrete construction for beams and slabs is the fact that it permits longer span lengths and more slender cross-sections than ordinary reinforced concrete construction. Figure 6-3, for instance, shows the variation in slab depth associated with conventionally reinforced concrete floor systems. These system ranges indicate that redesigning the parking garage with ordinary bar reinforcement would probably result in a slab depth of more than twelve inches, and FR1143 would not be satisfied.

However, a comparative advantage of conventionally reinforced concrete is its simpler construction sequence. Conventional concrete design permits a layered approach to placing reinforcing bars within the cross-section of a slab or beam. For instance, the construction process for a conventional concrete slab that is doubly reinforced with top and bottom bars can be represented by the following simple sequence of activities:

Formwork -> Bottom Bars -> Top Bars -> Concrete
FIGURE 6-3.
VARIATION IN DEPTH OF CONSTRUCTION ASSOCIATED WITH CONVENTIONALLY REINFORCED CONCRETE FLOOR SLAB SYSTEMS (30-FT. MAXIMUM SPAN LENGTH)
Based on analogy with above linear activity sequence, an innovative composite floor slab system is proposed. The concept sketch is shown in Figure 6-4 and depicts a sandwich-type floor slab made up of two high-strength, stiff faces separated by a core material. In terms of load-resisting capability, the advantages of sandwich structures are:

1. They permit uncoupling of the requirements for transfer of bending moments and shear.

2. They permit efficient engineering of cross-sectional properties.

Applied bending moments are equilibrated by the development of a force-couple within the planes of the faces. If the faces are much thinner than the core, their contribution to shear resistance can be neglected, and it can be assumed that the primary shear resistance is provided by the sandwich core. For a "efficient adhesive strength between the core and face panels, the bending capacity is a function of the strength and thickness of the faces, and the shear capacity is a function of the shear strength and thickness of the core material. Thus, sandwich structures permit the designer to vary independently the strengths of the face and core material. This flexibility improves the efficiency of the cross-section and accommodates a wide variation in engineering capabilities. In contrast, the shear and bending strengths of beams or slabs fabricated from a single base material, such as structural steel beams and reinforced concrete slabs, are inherently coupled as functions of a single material parameter and limited in range of application.
FIGURE 6-4. CONCEPT SKETCH OF PROPOSED SANDWICH-TYPE FLOOR SLAB SYSTEM
6.3 Reduced Inter-System Coupling

Review of the discussion provided in Section 5.4 on component design indicates that the Interface Index associated with construction process planning is equal to 265 links of information. This is a measure of the amount of information that must be exchanged between construction tradesmen in order to coordinate task execution in the field. These interfaces not only control the logical sequencing from tradesmen to tradesmen, but also affect the design of the individual components themselves so as to ensure constructibility. Since much of the design effort for detailing the components of subsystems is well documented and codified, the information content associated with the probability of satisfying the functional requirements in the physical domain is generally not significant, and the design complexity is dominated by the magnitude of the Interface Index. Consequently, this thesis refers to construction interfaces in the process domain as implicit or hidden couplings among the design variables created in the physical domain.

There are two or more options for reducing interface complexity in the process domain. The first option is to standardize the design of the interfaces so that the integration process can be preplanned with little uncertainty. The second is to reduce the degree of physical connectivity between coupled components.

6.3.1 Standardization

Standardization of design variables reduces the number of interface couplings in the process domain by expanding the tolerances associated with the process variables. This
permits the off-diagonal coupling terms of the design matrix to be neglected relative to the diagonal elements. Open building systems are examples of this philosophy, [4,7]. Open systems use standardized dimensions and component joining techniques so that subsystems can be freely chosen and installed from among a recognized catalog of building parts. Equation (6-1), for instance, presents the mapping between design variables and process variables for conventional construction of a network of steel floor beams intersected by electrical conduit.

\[
\begin{align*}
\begin{bmatrix}
DV1 \\
DV2 \\
DV3
\end{bmatrix} &=
\begin{bmatrix}
X & 0 & 0 \\
X & X & 0 \\
X & X & X
\end{bmatrix}
\begin{bmatrix}
PV1 \\
PV2 \\
PV3
\end{bmatrix}
\end{align*}
\]  

(6-1)

where:  
DV1 = wide-flange steel beams.  
DV2 = web opening.  
DV3 = electrical conduit.  
PV1 = erect structural steel.  
PV2 = cut and reinforce web holes.  
PV3 = install conduit.

Partitioning Equation (6-1) with respect to the structural (DV1,DV2) and electrical (DV3) subsystems yields an Interface Index equal to 2 links for information passing. This is the amount of overlap between the construction activities for the two subsystems. The coupling is due to the fact that proper installation of the electrical conduit is conditionally dependent on the cutting of holes through the webs of the steel floor beams. The technical complexity given by I=\log(1/p) can be quite large because the probability of success p for locating holes in the beam webs where required can be low due to the need to consider the impact of the requested hole size on loading conditions, localized stress fields, stability and
deflection criteria, and interactions between adjacent holes.

Replacing the wide-flange steel beams of Equation (6-1) with an innovative, open-web joist system reduces the interface complexity from 2 links to 0 links as shown in Equation (6-2).

\[
\begin{pmatrix}
DV1 \\
DV2
\end{pmatrix} =
\begin{bmatrix}
X & 0 \\
0 & X
\end{bmatrix}
\begin{pmatrix}
PV1 \\
PV2
\end{pmatrix}
\]

(6-2)

where:  
DV1 = open-web, steel joist.  
DV2 = electrical conduit.  
PV1 = erect structural steel.  
PV2 = install conduit.

The design matrix of Equation (6-2) indicates how the revised steel decking relaxes the degree of coupling between the structural and electrical subsystems. The electrical subsystem is no longer dependent upon cutting holes through beam webs. Thus, electrical conduit can be installed no matter how the joists are designed and erected. As a result, the design variable associated with the steel joists can be widely varied during the construction process without affecting the electrical conduits.

The sandwich slab proposed in the previous section is also an example of an open system. Using the core area as a devoted corridor for integrating the electrical conduits simplifies the interface conditions between the structural platform and the lighting system. Since the bending reinforcement is located on the slab exterior, interferences are minimized and subsystem integration efforts can be planned and executed with greater
certainty. This increased probability of success reduces the amount of information that must be exchanged among the responsible tradesmen and reduces the technical complexity of the construction process plan.

6.3.2 Reduced Physical Connectivity

The development of a strategy for reducing interface complexity by reducing the degree of physical connectivity requires a scale of measure. The American Institute of Architects [1], for example, identifies five levels of physical connectivity for building systems as shown in Figure 6-5. Remote is the first level of integration, and it refers to functionally coupled systems that are physically isolated from each other. Touching corresponds to systems that rest on top of one another and are held in place by gravity, while connected systems are secured to each other by physical connections. Meshed systems occupy the same space, and unified systems are physically integrated to the extent that they are indistinguishable from one another. In terms of system design, the latter four levels of integration, as indicated in Figure 6-5, are physical couplings that may or may not compromise the independence of the functional requirements. However, these physical linkages do create coupled or quasi-coupled construction processes because they establish contingencies for assembling the sets of components.

In the parking garage case study of Chapter 5, three levels of subsystem connectivity are identifiable: connected, meshed, and unified. For example, piping for the sprinkler system is connected to the underside of the floor slabs by pipe hangers; the conduit that carries the wiring for the lighting system is meshed with the cross-section of the floor slabs; and the facade as an aesthetic
FIGURE 6-5. LEVELS OF PHYSICAL INTEGRATION FOR BUILDING SYSTEMS
(AMERICAN INSTITUTE OF ARCHITECTS, [1])
feature is unified with the physical form of the parapet. All physical connections cannot be removed because the subsystems for fire safety, security, and aesthetics depend on the structural platform for physical support. However, connected systems are the simplest form of integration sufficient for maintaining the topology of the car park. Consequently, reducing the level of integration for the meshed and unified systems to connected is a suitable strategy for reducing inter-system coupling and the magnitude of the Interface Index.

Figure 6-6 is a review of the design matrix for mapping of the parapet/facade design variables to process variables. For simplicity, couplings with the structural platform have been removed in order to focus on the interface issues arising from the use of a unified form. As discussed in Section 5.4, the Interface Index derived by partitioning the 3x9 design matrix is equal to 17 links for information passing. In addition, the location of the coupling terms within the design matrix suggests that the use of a unified element for the parapet/facade acts as a bottleneck during field activities related to the placement of concrete. This observation has been validated through discussion with the contractor's Project Manager for Field Operations.

Although the process variables pertaining to construction of the parapet as a vehicle barrier and to the facade as an aesthetic feature can be identified through a systematic, functional breakdown, the inter-system couplings limit the designer's freedom to vary the design of each subsystem as functional requirements are varied. The information content $I=\log(1/p)$ for construction of the parapet/facade is large as a result of the small conditional probabilities associated with the off-diagonal
FIGURE 6-6.  DESIGN EQUATION GOVERNING MAPPING OF DVs TO PVs FOR CONSTRUCTING COMPONENTS OF PARAPET/FACADE
terms of the design matrix. The conditional probabilities are small because of the tight tolerances imposed on the visual quality of the composite element. Refer to Section 5.4 for additional discussion of the relevant construction problems.

Covering the exposed face of the parapet with modular panels fabricated from either red granite or precast architectural concrete is a solution alternative that converts the unified structure into a system of connected elements. Figure 6-7 shows the design equation for construction of this modified solution. The net effects are an increased modularity of construction, which permits a wider variation in physical appearance, and a reduction in Interface Index from 17 links to 9 links of information. Note that 5 of the 9 links of information reflect the fact that securing the panels in situ is conditionally dependent upon successful construction of the parapet. However, the information content associated with these conditional probabilities is not as large as for the original design because uncoupling the concept of visual quality from the task of parapet construction increases the contractor's allowable variation.

6.3.3 Proposed Design Solution for Reduced Interface Complexity

Table 6-1 is based on Table 5-7, and it provides a breakdown of the component-level interface measures associated with construction of the original garage design. We see from Table 6-1 that the interface complexity during construction planning is dominated by subsystem linkages arising from aesthetic requirements and the requirement for a structural platform. Some of the more significant linkages are summarized below.
Figure 6-7. Design equation for construction of proposed solution to reduce interface complexity of parapet/facade.
<table>
<thead>
<tr>
<th>Subsystem Linkage</th>
<th>Interface Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire Safety:Security</td>
<td>13 links</td>
</tr>
<tr>
<td>Fire Safety:Aesthetics</td>
<td>0 links</td>
</tr>
<tr>
<td>Fire Safety:Structural Platform</td>
<td>56 links</td>
</tr>
<tr>
<td>Security:Aesthetics</td>
<td>29 links</td>
</tr>
<tr>
<td>Security:Structural Platform</td>
<td>111 links</td>
</tr>
<tr>
<td>Aesthetics:Structural Platform</td>
<td>56 links</td>
</tr>
<tr>
<td><strong>Total Interface Complexity</strong></td>
<td><strong>265 links</strong></td>
</tr>
</tbody>
</table>
1. Task dependencies associated with mounting the sprinkler system (fire safety) on the concrete columns and post-tensioned floor slab system of the structural platform.

2. Physical integration of aesthetic facade details with the parapet provided for vehicle security.

3. Monolithic joint construction between the parapet/facade (security and aesthetics) and the post-tensioned floor slab system.

4. Physical integration of the lighting system (security) within elements of the structural platform.

Table 6-2 summarizes the revised interface measures resulting from implementation of the proposed sandwich slab floor system and the modular facade panels. The reduction in the security:structural platform linkages reflects the use of the sandwich slab's core area as a standard interface for integrating elements of the lighting system. The simplified construction sequence for the sandwich slab as compared to post-tensioned, reinforced concrete construction also reduces the number of task dependencies associated with the installation of the sprinkler system (fire safety) and the connection of the protective parapet (security).

As discussed previously, the switch to modular facade panels uncouples the visual quality of the facade (aesthetics) from the construction of the protective parapet (security). In addition, the modular panels also reduce interface complexity by reducing the number of design variables that must be considered while physically connecting the parapet to the edges of the floor slab system.
TABLE 6-2. COMPARISON OF INTERFACE COMPLEXITY MEASURES FOR THE ORIGINAL AND REVISED PARKING GARAGE DESIGNS (CONSTRUCTION PLANNING AT COMPONENT LEVEL)

<table>
<thead>
<tr>
<th>Subsystem Linkage</th>
<th>Interface Index</th>
<th>Original Design</th>
<th>Revised Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire Safety:Security</td>
<td>13 links</td>
<td></td>
<td>13 links</td>
</tr>
<tr>
<td>Fire Safety:Aesthetics</td>
<td>0 links</td>
<td></td>
<td>0 links</td>
</tr>
<tr>
<td>Fire Safety:Structural Platform</td>
<td>56 links</td>
<td></td>
<td>31 links</td>
</tr>
<tr>
<td>Security:Aesthetics</td>
<td>29 links</td>
<td></td>
<td>12 links</td>
</tr>
<tr>
<td>Security:Structural Platform</td>
<td>111 links</td>
<td></td>
<td>74 links</td>
</tr>
<tr>
<td>Aesthetics:Structural Platform</td>
<td>56 links</td>
<td></td>
<td>12 links</td>
</tr>
<tr>
<td>Total Interface Complexity</td>
<td>265 links</td>
<td></td>
<td>142 links</td>
</tr>
</tbody>
</table>
6.4 Improved Performance with New Technology

In creating the ideas for the sandwich slab and the modular facade panels, the need to reduce coupling took precedence over consideration of current technological capabilities. Clearly, if the required technology to effectively implement these ideas is not available, the practicing designer must compromise and rely on available solution strategies. However, the process of making technological needs explicit is essential for stimulating investment in the basic research necessary to advance the capabilities of the industry. Industry-wide diffusion of performance criteria and market competition between the producers of building elements can shorten the time-lag between the initial expression of need and the development of the technological potential to fulfill the need.

Masonry walls and pillars, for example, were the only construction technology available for large buildings until the mid-nineteenth century, [11]. The bigger the building, the thicker the stonework had to be. As a result, buildings rarely went beyond five or six stories. In addition to carrying the deadweight of the entire structure and any imposed live loads, the massive masonry walls enclosed and protected the interior environment. Thus, building envelope technology was not really needed beyond the use of glass windows. New York's Pulitzer Building, for instance, was built in 1890 and was one of the last to depend on load-bearing masonry walls. With fourteen stories, its external walls were nine feet thick at the base.

Then, in the mid-1800's, along came iron and the discovery of skeleton construction for framing high-rise structures. With the use of beam-and-column framework, the structural
frame is no longer capable of protecting the interior environment. It only performs a load-bearing function. This functional transition stimulated the demand for the development of building envelope systems as independent entities for sealing, insulating, and aesthetically wrapping the building structure. The capability to decouple the structural frame and envelope has enabled the height of skyscrapers to increase from the 180-ft. tall, 10-story Home Insurance Building completed in 1885 to the 1454-ft. tall, 110-story Sears Tower completed in 1974. Thus, the twentieth century has seen the advancement of glass technology from a filler material between massive frame elements to a thin skin providing thermal insulation, weather protection, and aesthetic features [11].

Adoption of parking garages as a constructed system with characteristic functional features and service-life requirements may stimulate investment in innovative floor slab technology. For instance, the use of sandwich slabs as an effective alternative to prestressed concrete slabs is largely dependent upon the strength and stiffness requirements for the top and bottom faces. Least-weight design [3] of a sandwich panel subject to a stiffness constraint and a given core design indicates that optimum design of the faces requires minimizing the mass density-to-elastic modulus ratio, $\rho/E$. Similar analysis with regard to yielding of the sandwich faces [3] establishes minimum mass density-to-yield strength ratio, $\rho/\sigma$, as the optimality criterion.

Table 6-3 summarizes the ratios $\rho/E$ and $\rho/\sigma$ for various materials. The tabulated data is extracted from Reference 2. Based on the data of Table 6-3, carbon-fiber reinforced polymer (CFRP) offers the best performance for
<table>
<thead>
<tr>
<th>Material</th>
<th>Density ρ (kg/m³)</th>
<th>Yield Strength σ (MN/m²)</th>
<th>Elastic Modulus E (GN/m²)</th>
<th>ρ/σ (kg/MN-m)</th>
<th>ρ/E (kg/GN-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>7800</td>
<td>248-400</td>
<td>196-200</td>
<td>19.5-31.5</td>
<td>39.0-39.8</td>
</tr>
<tr>
<td>Concrete</td>
<td>2500</td>
<td>25-70</td>
<td>45-50</td>
<td>35.7-100</td>
<td>50.0-55.6</td>
</tr>
<tr>
<td>Wood</td>
<td>400-800</td>
<td>35-55</td>
<td>9-16</td>
<td>11.4-14.5</td>
<td>44.4-50.0</td>
</tr>
<tr>
<td>Aluminum</td>
<td>2700</td>
<td>40-627</td>
<td>69-79</td>
<td>4.31-67.5</td>
<td>34.2-39.1</td>
</tr>
<tr>
<td>GFRP</td>
<td>1400-2200</td>
<td>100-300</td>
<td>7-45</td>
<td>7.33-14.0</td>
<td>48.9-200</td>
</tr>
<tr>
<td>CFRP</td>
<td>1500-1600</td>
<td>640-67</td>
<td>70-200</td>
<td>2.34-2.39</td>
<td>8.00-21.4</td>
</tr>
</tbody>
</table>
least-weight design of the faces for the sandwich slab, followed by aluminum and steel. Practical use of CFRP as external reinforcing has been limited to applications for structural rehabilitation due to its prohibitive cost and concerns over premature material degradation. However, ongoing research at the Federal Highway Administration in Washington, D.C. has been focusing on the development of fiber-reinforced plastic bridge decks resistive to chemicals and de-icing salts, [6]. Currently, these decks can only be manufactured by hand-laminating techniques. Thus, the manufacturing process for CFRP panels is a target for additional research and development because the current process is small-scale, labor intensive, and reliant on highly skilled labor.

Metals, such as aluminum and steel, have poor service life performance in corrosive exposure conditions, [5]. Therefore, they are impractical as external faces of a sandwich slab for a parking garage with an intended 50-year service life. However, the concept of high fiber-reinforced concrete enhances the durability of concrete while advancing its mechanical properties closer to those of metals. Danish researchers, for example, have tested a concrete beam with a 20% volume of fibers, and it behaved like a conventional steel beam, [9]. Concrete building materials are currently available with a fiber volume of less than 1%, but high fiber-reinforced concrete contains a fiber volume of more than 10%. The higher volume fractions of fibers produce a concrete that is more ductile with dramatically improved resistance to fracture and cracking. In the U.S., researchers at the National Science Foundation's Center for Advanced Cement-Based Materials are experimenting with concrete mixtures containing a fiber volume between 10% and 12%, [9].
One futuristic solution strategy for developing a composite sandwich slab for parking decks is to use high fiber-reinforced concrete panels for the top face and CFRP panels for the bottom face. This is a more effective use of the CFRP because it is removed from the area of most severe exposure and replaced by an inherently more durable material. Joint use of CFRP and high fiber-reinforced concrete also would cost less than the exclusive use of CFRP panels. Process innovations for fabrication of the composite slab, however, are required to ensure product quality, product uniformity, large-scale production volumes, and simplified construction.
6.5 References


Chapter 7 Strategy for Implementation

7.1 Introduction

Previous chapters have advanced and demonstrated the concept of performance-based design as a methodology for improving the quality of complex, multi-disciplinary projects. A quality facility is one that optimally satisfies the performance requirements of the client/owner. In terms of life-cycle considerations, these performance requirements can include a number of diverse issues, such as serviceability, reliability, durability, ease of construction, and ease of maintenance. The delivery of a quality project draws upon the contributions from two distinct groups within the building industry: product designers and those agents who operate on the completed design. Clearly, architects and engineers comprise the group of product designers, while construction firms and maintenance managers constitute design operators. Construction firms are further separable into the general and specialty contractors responsible for the fabrication and assembly of building elements.

As the demands on a product or a facility increase, it is a truism that both the cost and the value of achieving additional functional requirements increase. The challenge of performance-based design, therefore, is to strategically satisfy a breadth of functional requirements while ensuring that the resulting project costs no more than it is really worth. Thus, project quality must be obtained at a minimum cost, and care must be taken to avoid overdesign. The following, simple cost model provides a framework for discussing the effects of increased performance on project cost [1]:

272
\[ C = (m + mw) + (l + lt) \]  (7-1)

where:  
\( C \) = direct construction costs for a given quality of construction.
\( m \) = material costs.
\( l \) = basic labor and equipment costs.
\( w \) = factor which relates variations in material resources due to uncertainty to material costs.
\( t \) = factor which relates variations in construction time due to uncertainty to basic labor and equipment costs.

Equation (7-1) states that direct construction costs are given by the sum of material costs and basic labor and equipment costs. Material costs vary with the resources needed for procurement (including allowance for wastage). Labor and equipment costs are time-dependent, varying with the time required for construction. Based on the above cost model, an increase in performance can lead to an increase in cost due to one or both of the following reasons:

1. Greater uncertainty in material processing due to novel specifications for improved durability, reliability, and maintainability requirements.

2. Greater uncertainty of tasks for labor and equipment due to novel configurations and performance specifications.

According to the Information Axiom [28], the greater the uncertainty associated with a task, the greater the amount of information that has to be processed during task execution. If the task is well understood, much of the activity is predictable and can be supported by routine knowledge and procedures. If it is not well understood, the activity evolves dynamically as new knowledge and
procedures are learned. To ensure an effective and competitive project delivery process, this chapter presents an implementation strategy for performance-based design that supports increased information processing in terms of design management and design support.

First, an organizational structure for the project participants is designed. The requirements of the organizational structure are to manage the delivery process and to support the collaborative exchange of information between the participants. The governing criterion for organizational structure is to minimize the costs associated with coordinating inter-related activities.

Second, a computer system is offered as an enabling technology to increase the information processing capacity of the project team. This capacity should be matched to the level of uncertainty for the delivery process. Therefore, system architecture is based on a set of functional requirements pertaining to documentation, group collaboration, and decision-making.

7.2 Organizational Complexity

A key aspect of performance-based design is recognition of the fact that total performance must be evaluated in a systems-context because it is derived from the contributions of the various project personnel and the interactions among these outputs. The structure of the project team provides a framework for coordinating the activities of the various agents. Designers and design operators should be organized so as to minimize coordination costs, thereby reducing organizational complexity, [29]. Thus, optimal organization of the
project team is equivalent to minimizing the information content per the Information Axiom [28].

Although there is no absolute scale for measuring the coordination costs associated with a particular structuring scheme, the concepts of Organization Theory as advanced by Thompson [29] provide a basis for reasoning about the relationships between organizational structure and coordination complexity. Obviously, the design of an organizational structure so as to simplify coordination is dependent upon the nature of the interdependencies occurring among the organization's members. Therefore, the first step is to develop an understanding of the interdependencies associated with the project team.

In general, interdependencies fall into one of the following categories [29]:

1. Pooled.
2. Sequential
3. Reciprocal.

They are shown schematically in Figure 7-1.

Pooled interdependence is the simplest relationship. Departments of an organization that have pooled interdependence contribute to the performance of the whole and are supported by the whole; however, they do not interact at all with each other. As a result, the departments tend to draw upon a common pool of resources and/or their contributions tend to combine in an additive manner. For instance, the plumbing and electrical engineers for a building can be viewed as a pooled interdependence: their outputs are functionally isolated, yet both contribute to the serviceability of the completed facility and draw upon the available interstitial space.
FIGURE 7-1. TYPES OF ORGANIZATIONAL INTERDEPENDENCIES
When departments have sequential interdependence, the output of one department is directly dependent upon input from the other. In the construction domain, for example, the relationship between the steel fabricator and the ironworkers is a sequential or serial interdependence. The steel fabricator transforms raw steel into various shapes and components for construction. These products are then delivered to the ironworkers on site for erection. There is also a pooled aspect to the fabricator/ironworkers relationship because both parties contribute to and are sustained by the project as a whole. Thus, the need to sequence fabrication and assembly activities adds another layer of complexity to construction operations.

Two departments whose functions directly affect the other have a reciprocal interdependence. The outputs and inputs are coupled so that the performance of each department is dependent upon the other. Structural designers and concrete contractors are examples of project groups that can share a reciprocal interdependence. The necessary construction technology, such as formwork and concrete placement strategy, cannot be established until the structure is designed; however, the process of designing a concrete structure for ease of construction requires input or feedback from the construction domain. Reciprocal interdependence is the most complex relationship because it also includes elements of pooled and sequential interdependencies. Clearly, the resources and decisions of both the structural engineer and the concrete contractor draw upon the project's financial resources and their decisions must be logically sequenced for optimum performance.
Three coordination techniques parallel the above forms of interdependence, [29]: standardization, planning, and mutual adjustment. Coordination by standardization relies on established routines or standards to constrain the output of each department involved in a pooled interdependence, [29]. Standards simplify coordination by creating a consistent protocol for aggregating the contributions of various agents into a total system. In the building industry, prefabricated items, such as windows, doors and frames, and wall units, are examples of standardized building elements that can be selected and assembled in many different ways, [13]. Industry practice with respect to dimensions and connection techniques is relied upon to resolve interfaces between building components.

Coordination by plan relies on scheduling to queue the actions of departments that are sequentially interdependent. The project schedule integrates and coordinates all preceding and succeeding activities within an interdependent sequence. For example, the construction schedule is traditionally prepared by the general contractor who is responsible for controlling project construction. He must identify, sequence, and codify the necessary construction tasks. The resulting schedule provides a framework for managing the various fabricators and trade contractors that actually build the project so that all elements and labor needs flow in a smooth and logical sequence, [7].

The concept of mutual adjustment involves both the forward and backward feeding of information between departments that share reciprocal interdependence, [29]. Due to project uniqueness and the use of original design concepts, decision-making may be sufficiently
unpredictable so that pre-established rules or plans are not effective. As a result, a problem-solving approach is adopted, and the coupled departments interact in a manner that is problem-driven, [1]. One can intuitively appreciate that coordination by mutual adjustment is the most costly in terms of demand on organizational resources and standardization is the least costly, [29].

7.3 Organizational Structure for Project Team

Figure 7-2 summarizes the nature of the dependencies occurring among the various members of the project team for the delivery of a constructed facility. The design problem is to structure the project team so as to minimize coordination costs. Since priority must be given to facilitating communication among those departments that require coordination by mutual adjustment [29], parties with reciprocal interdependence are grouped together first. Second priority must be given to those members with sequential interdependence, and any remaining parties with pooled interdependence are grouped together last. Consequently, the proposed project structure for performance-based design is shown in Figure 7-3. The nature of the interdependence varies with hierarchical level. The first-order groupings capture the sequential interdependencies among the process planning, fabrication, and assembly agents of the construction organization. The second-level groupings couple the reciprocally interdependent project designers (architects and engineers) and operators (construction and maintenance managers) with the office of the project manager.

To the client/owner, the tripartite level consisting of designers, operators, and project manager spans the basic areas of project performance: services, aesthetics, and
FIGURE 7-2. CLASSIFICATION OF INTERDEPENDENCIES AMONG PROJECT TEAM MEMBERS
FIGURE 7-3. PROPOSED PROJECT STRUCTURE FOR PERFORMANCE-BASED DESIGN
economics. The project manager represents the interests of the client/owner in terms of project requirements and provides a control center for the project delivery process. As an integrative agent, his responsibilities include the assembly of comprehensive design matrices to aid decision-making in the physical and process domains. If there is a design or construction problem, all affected requirements and design variables rise to the level of the project manager, who is a shared superior for all affected parties. A collaborative decision is made, and the new requirements or design variables are brought back down to the level of the evolving design. Thus, decisions concerning the resolution of design and construction interface issues can be addressed in the context of overall project performance.

The project structure shown in Figure 7-3 is similar to the organizational strategy adopted by Boeing for introducing the 747 airplane in the mid-1960's, [9]. The introduction of new models in a complex, vertically-integrated firm such as Boeing involves highly uncertain and interdependent tasks during the design and production cycle. For Boeing, the design and production cycle involves the progression of an aircraft from concept to product design to process design to purchasing to fabrication and assembly. Prior to about 1964, Boeing faced little direct competition in the commercial, jet aircraft market, [9]. Therefore, it was able to rely on long project lead times as a buffer for dealing with uncertainty and task interdependency, i.e., research and development was used to eliminate much of the coupling between product design and process design. During the considerable amount of time devoted to prototype development, the reciprocal interdependence between the
design and process groups was reduced to sequential interdependence prior to final design and production, [9].

After 1964, however, Boeing's markets for jet aircraft came under direct competition from various domestic and European competitors, [9]. Boeing's response to this competition was to shorten the design and production cycle by integrating design and manufacturing tasks. Thus, the 747 project could not rely on the lead times enjoyed by past projects. The reciprocal interdependence between the design and process groups had to be dealt with effectively. To support integration of the 747 program, Boeing adopted the project structure shown in Figure 7-4. The office of the program manager had access to a large amount of detailed information concerning design and production tasks and had a large amount of decision-making power. Detailed program information provided the capacity to identify all tasks affected by a particular problem, allowing cause and effect relationships to be traced. Aided by this information, the program manager could call a meeting of the corresponding managers so as to promote collaborative problem resolution.

7.4 Functional Requirements for Computer-Based Support

The integrated, project team structure outlined in the preceding section is quite similar to recent advances in alternative project delivery methods, such as design/build, turnkey, and modular, fast-track construction. By contracting a project team, design and construction activities can proceed concurrently, resulting in an accelerated project schedule and reduced delivery costs in comparison with traditional, fragmented, over-the-wall approaches. Alternative delivery methods originated in the private sector for development of mega-
FIGURE 7-4. BOEING PROJECT STRUCTURE FOR THE 747 PROGRAM
(GALBRAITH, [10])
projects, such as power plants and industrial facilities, [23]. However, taxpayer dissatisfaction with long construction schedules and cost overruns has stimulated a growing demand for the use of alternative delivery methods in the public sector. Recent articles [3,23] cite public-financed projects involving design/build and turnkey bid proposals in the areas of transportation infrastructure, prisons, and sports facilities.

The proposed methodology for performance-based design gives a structured, hierarchical, and integrated approach to the project delivery process. The process of functional decomposition, mapping, and zig-zagging between design domains provides an organized framework for project delivery that can increase the competitive advantage of design/build, turnkey, and modular, fast-track construction strategies in the areas of performance merit and constructibility.

**Performance Merit**

In addition to bid estimates, the concepts of functional requirements and information content provide rational criteria for comparing competing proposals. Owners have embraced alternative delivery methods as a means to improve project performance with respect to cost and scheduling. However, it is not clear as to whether there has been any gain in project effectiveness with respect to other performance requirements, such as serviceability, durability, ease of maintenance, etc. Since the industry is dominated by projects with short deadlines and disproportionately large workloads, engineers tend to rely on point designs, [21]. That is, they modify the details of past designs so as to suit the particular uniqueness of the job at hand, rather than adopting a rigorous, top-down approach.
Reliance on point designs shifts design emphasis to ensuring code compliance with regard to safety and reliability. Less time and resources are devoted to the process of searching for and selecting appropriate solution concepts. As a result, designers internalize their intentions, and there is a considerable lack of documentation concerning project history. Performance-based design, on the other hand, seeks to articulate and quantify at all levels of abstraction the relationship between the functional requirements and the design variables. Thus, the decision-making process is externalized and continuous documentation for the project is generated.

**Constructibility**

Figure 7-5 is a matrix representation of the project delivery process in the Japanese design-build industry, [14]. The matrix outlines the scope, responsible agents, and output associated with each phase of the delivery process. Scope defines the tasks necessary to ensure the project's progression from conception to construction to operation and maintenance. The responsible agents are the members of the project team involved in the decision-making process, and output summarizes the types of information that are generated. In this context, the architect's role is limited to developing functional layouts and providing aesthetic features rather than the traditional, supervisory role.

The weakness of this project delivery scheme is the fact that the integration of the construction manager with the architectural and engineering personnel is not established until the detailed design phase. Consequently, the scope of the construction manager's input to the design process
<table>
<thead>
<tr>
<th>CONCEPTION</th>
<th>PLANNING</th>
<th>ROUGH DESIGN</th>
<th>DETAIL DESIGN</th>
<th>CONSTRUCTION</th>
<th>MAINTENANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investigation • Analysis of Design Contents • Confirmation of Condition</td>
<td>Selection of Structure Type • Cost Study • Determination of Ground Classification</td>
<td>Analysis • Design Feedback • Estimation of Rough Cost</td>
<td>Detail Drawing • Estimation of Detail Cost • Selection of Construction Methods</td>
<td>Management of Construction • Construction • Safety</td>
<td>Maintenance</td>
</tr>
<tr>
<td>AGENTS</td>
<td>Owner • Sales • Architect</td>
<td>Owner • Sales • Architect • Cost Estimator • Structural Engineer</td>
<td>Owner • Sales • Architect • Cost Estimator • Structural Engineer • Mechanical &amp; Power Engineer</td>
<td>Architect • Cost Estimator • Structural Engineer • Mechanical &amp; Power Engineer • Construction Manager</td>
<td>Construction Manager • Sub Constructor</td>
</tr>
<tr>
<td>OUTPUT</td>
<td>Minutes • Investigation Report • Rough Sketch</td>
<td>Planning Report • Cost Plan</td>
<td>Rough Cost • Rough Drawing • Result of Structure Analysis • Mechanical &amp; Power Design</td>
<td>Detail Cost • Detail Drawing</td>
<td>Construction Drawing • Construction Schedule • Construction Logs • Management Info</td>
</tr>
</tbody>
</table>

FIGURE 7-5. PROJECT DELIVERY PROCESS IN JAPANESE DESIGN/BUILD INDUSTRY
(IMAI AND TAKAGI, [15])
is limited to conducting critical analysis of specific design details after most of the major design decisions have been made. Since upwards of 80% of the final cost may be committed before the rough design is finalized [8], integrating architectural, engineering, and construction personnel during the detailed design phase only impacts about 20% of the project cost. Clearly, an advanced delivery process requires merging design, construction, and maintenance technology earlier in the project cycle.

In contrast, performance-based design supports concurrent consideration of design and construction issues by requiring the designer to zig-zag between design domains. The evolving design descriptions in the physical domain must be mapped to a corresponding set of construction systems in the process domain prior to the creation of lower-level functional requirements and design variables. Zig-zagging provides constructibility feedback to the designer, and it also feeds constructibility issues forward since construction planning decisions establish a context or a set of constraints for subsequent design decisions.

Despite the above benefits to performance merit and constructibility, it may be difficult for the concept of performance-based design to compete with point design on the basis of comparative design costs or schedules. Performance-based design can increase design costs and/or extend the design schedule by requiring designers to clarify functional requirements at all levels of abstraction and to systematically select the best solution. This problem is exacerbated by the lack of comprehensive documentation from past experience. Since limited data is available to prune the solution space,
considerable time and effort is required to generate, characterize, and evaluate candidate solutions. Consequently, the wide-ranging adoption of performance-based design requires enabling computer-based technology so as to reduce the time necessary for the additional design effort.

The development of a computer-based support system for performance-based design must satisfy the following set of functional requirements:

1. Capture project history.
2. Support collaboration among members of project team.
3. Support the decision-making sequence.

These three requirements are discussed below.

7.4.1 Capture project history

Design can be viewed as a translation process [28], and the successful translation of abstract owner/user needs to an operating facility depends upon the project team's ability to generate, store, and retrieve various forms of information. Knowledge is needed to recognize, interpret, generate, and utilize project information so as to deliver a completed facility to the owner/user. Thus, the project history involves an interweaving of information and knowledge.

Information refers to the project-specific functional requirements, design variables, process variables, drawings, specifications, and documents. The information generated at each level of abstraction feeds forward to subsequent design levels. Knowledge can be analytical or experiential. Analytical knowledge refers to the data, rules, and algorithms pertinent to each member of the
project team. Experiential knowledge is captured in the human mind and is generic to all similar projects. Together, these two types of knowledge establish the capabilities of the project team and provide annotation for project information. This annotation can consist of text, graphic diagrams, videos, or group discussions. The diversity of the information sources means that the project history cannot be adequately captured by one storage medium.

7.4.2 Support collaboration among members of project team

Historically, drawings are the media of communication between construction industry participants. They represent a significant portion of the output generated within each phase of the project delivery process. Drawings are relied upon to communicate information between different members of the project team and to link activities between different project phases. Drawings also support localized design activities. For the working designer, drawings provide a readily manipulable model of the relationships between the various sub-systems and components that comprise a system, [18]. They enable designers to deal with the large amounts of complexity associated with the following cognitive processes: reasoning about a particular configuration, developing alternative configurations, and exploring new options.

CAD packages, for example, permit the contributions from multiple disciplines to be superposed as two-dimensional drawings in order to aid in identifying geometrically incompatible layouts and configuring interfaces for operation and maintenance activities. COMANDS [4], developed by Stone & Webster Engineering Corp., is an integrated three-dimensional modelling system that links
graphic information to a database containing information on design, construction, and operation. It supports constructibility reviews concerning interferences, erection sequences and crane positioning, and it also generates construction schedules.

Unfortunately, the role of COMANDS [4] and other CAD packages is limited to representing and integrating low-level design information consisting of component configurations and dimensions. As a medium for communication, CAD has been seen to decrease and inhibit group interactions versus traditional drawing boards, [15]. While drawing boards have provided a backdrop for face-to-face meetings among design contributors, the CAD workstation is perceived as an individual workspace, providing graphical information about a small portion of the total design. Only when the subsystems of a project are identified can tasks be split up among design disciplines and the associated CAD drawings be prepared, [18]. Consequently, current CAD technology does not support the earlier stages of design where many minds must interact to develop and envisage the design as a whole.

7.4.3 Support the decision-making sequence

The decision-making sequence is separable into the following set of activities:

2. Evaluation of solution alternatives.
3. Selection of a solution alternative.

Execution of the sequence involves two capabilities for knowledge processing: black box and glass box, [18]. Black box processes include the intuition and insight necessary for design synthesis. Synthesis is an
internalized activity that relies on elements of creativity, past experience, analogy, etc. to generate solution concepts. While advances in artificial intelligence have created new possibilities in computer-based synthesis, the creative, black box processes are best performed by people. Compared with computers, intuition and insight are possibly the most valuable and superior faculties of the human mind, [19].

Once a possible solution or set of solutions is defined, glass box processes are used to determine both the amount of coupling and the suitability of solution performance. These determinations are made relative to the stated functional requirements. Most glass box processes are based on the following concepts: scientific laws, applied mathematics, and modelling and simulation. While the human mind is severely limited in terms of its ability to reason about multivariate systems, computer technology is continually advancing its superiority in the areas of computational capacity, processing speed, and reliability.

Since neither the human mind nor the computer is best suited for both black box and glass box processes, the natural role for the human–computer interface during the decision sequence is symbiotic: the computer can supplement the human mind during creative, black box activities and support solution evaluation and selection by dealing with tedious, computationally-intensive glass box processes, [19]. The following section outlines a system architecture for application of enabling computer-based technology.
7.5 Computer-Support System for Performance-Based Design

A system architecture to support performance-based design is shown in Figure 7-6. Each member of the project team can access and interface with the project memory, which is stored within a hypermedia system [5,16]. The decision-making sequence is supported by a distributed network of workstations that can access the project history and perform design characterization studies. A Knowledge media network [16,26,27] provides a collaborative environment for face-to-face meetings. This environment supports brainstorming, exchange of information and knowledge, and the resolution of interface issues. Knowledge media tools also support the concept of project management by exception [9]: problems that cannot be resolved through application of rules for standardization or changes in project schedule are resolved through face-to-face meetings. The major elements of the system architecture are discussed below.

7.5.1 Hypermedia System

Hypermedia systems [5] are information management systems that support storage and retrieval of text, graphic, audio, and video forms of information. Based on Vannevar Bush's concept of a "memex" [2] for storing data in a manner similar to the human mind, hypermedia systems preserve data in a network of nodes connected by links. The internodal connections are based on an associative structure established by the system's author, and they permit nonlinear traversal of the dataspace.
Current commercial, hypermedia systems have two or more weaknesses that limit their robustness for design, [10]:

1. Lack of query-based access to hypermedia networks.
2. Inability to aggregate basic node and link models into composite nodes or objects.

First, query-based access refers to an information-retrieval scheme that permits the user to request information by questioning the hypermedia system. The system would then be capable of intelligently locating the target information in its data network. Ideally, hypermedia systems would provide users with the same capabilities researchers already enjoy in libraries, [16]. Traditional card catalogues and compendia of science and engineering publications are examples of hypertext systems. Each user enters the referral system at a different location depending upon his topic of interest. For any subject, a unique path of inquiry can be followed by searching among keywords and cross-referenced listings and browsing through serendipitous references. The process continues until the user finds a suitable book, publication, or journal article.

Dependence on internodal links as a means for accessing multimedia data, however, hinders system flexibility for information retrieval. The available paths for browsing and navigation within the network are restricted to prior associations made by the network author. One benefit to capturing project history is the fact that it provides the project team with a "group memory" so that information can be retrieved and reviewed by each participant, [17]. Since the project team is comprised of diverse disciplines and perspectives, the retrieval method must accommodate diversity. In addition, the designers of future projects who are seeking to access the memory of a past project may
be unfamiliar with and frustrated by the chosen strategy for grouping and linking design information.

Second, the ability to create composite nodes allows various information units to be clustered into a higher level object. This means that design decisions can be preserved more naturally as a system of objects. In addition, a wider range of information queries can be supported. Object-oriented data storage enables each member of the project team to ascribe pertinent information to a design artifact so that the effects of collaboration are not lost.

The PHIDIAS project [22], for example, is a prototype hypermedia system for computer-aided design that supports both query-based access and the construction of higher-level objects. Developed to accommodate the needs of architectural, interior, landscape, and urban designers, PHIDIAS interactively processes graphic and text information. It demonstrates the potential documentation advantage that hypermedia systems offer over conventional computer-aided design (CAD) systems: hypermedia permits annotation of graphical data with causal reasoning and illustration of text with visual images.

PHIDIAS' graphical interface permits the designer to shape a physical solution by selecting, manipulating, and positioning artifacts from a palette of building blocks onto a two-dimensional workspace. Each building block represents a node in the hypermedia network. Sinks, stoves, refrigerators, and cabinets are examples of building blocks supporting interior design. Particular layouts or patterns of building blocks can be assembled into graphical clusters or composite objects, such as a "kitchen", and these composite objects are also stored as
nodes in the data network. Text is used to provide argumentation for design decisions. It can be clustered with the graphical building blocks and objects. The system also includes an overhead computational capability that performs active processing of information, allowing the system to critique the actions of the designer by posting domain-specific issues for consideration. The intent of these knowledge-based criticisms is to help the designer see the pros and cons of decisions, as well as reduce the potential for major errors.

Consider the selection of a particular style of refrigerator, [22]. Selecting a refrigerator from the palette of available styles elicits useful information related to capacity, operation, access requirements, and heuristics for efficient positioning within a kitchen layout. These are issues that the designer must resolve during placement in the evolving kitchen layout. As a result, the graphical elements are annotated by both the designer's reasoning and the knowledge-base inherent to the PHIDIAS system.

PHIDIAS provides a structured language for query-based access of network information. This English-like language relies on operational primitives that can be combined to form complex queries. The system supports both structure-based and content-based retrieval [10]. These are natural retrieval concepts because structure and content are two simple ways of characterizing the data network. Structure refers to the composition and linking of the stored information; content refers to the actual information that is stored. Consequently, structure-based retrieval provides direct access to a particular spatial location or node type within the hypermedia network. Content-based retrieval involves intelligent scanning of the dataspace.
so as to match the target information with a corresponding unit of stored information. Since both graphical and textual information are assigned to nodes in the PHIDIAS network, they can be accessed by structure-based queries. PHIDIAS also permits content-based retrieval of text information. This involves comparing the search or target string with stored character strings, [22].

Content-based retrieval of audio, graphic and video forms is more problematic than the treatment of text. Understanding the content of audio information requires an ability to recognize and process natural language. Although the ambiguity of natural language retards machine advances in this area, there has been some success in developing natural language interfaces for accessing databases [11,12] and text documents [20]. Content-based access of visual data is a wide open research field because the information captured in images can have as many interpretations as there are viewers. Thus, significant advances in the development of intelligent hypermedia systems can be linked to advances in tools for recognition, manipulation, and understanding of information stored in audio and visual forms.

7.5.2 Knowledge Media

The concept of knowledge media [16,26,27] refers to the use of artificial intelligence (AI) to support face-to-face meetings where visual information is presented for collaboration. In contrast to relying on AI to provide robust, stand-alone systems capable of dealing with complex and uncertain environments, the knowledge media approach focuses on the development of intelligent environments for enabling communication, [16].
Since the members of the project team have differing frames of reference, there is a high level of ambiguity associated with defining and resolving problems. Face-to-face meetings are a rich medium for supporting discussion and developing a shared understanding, [6]. The richness of face-to-face meetings is based on the fact that they allow rapid feedback and support multiple views for exchanging information, such as language and personal focus. Therefore, the concept of knowledge media seeks to improve those aspects of meetings that are annoying and a hindrance to productivity, such as the need to erase the meeting's chalkboard to accommodate increased information, a shift in meeting focus, or a rearrangement of the posted information, [27]. Each chalkboard erasure represents a loss to the collaborative effort in terms of time and information, as well as lost opportunity for creative interaction.

The Colab Project [26,27] at XEROX's Palo Alto Research Center, for example, is an experimental implementation of the knowledge media tools. It is an electronic meeting room that supports collaboration among two to six people. Each person has a workstation connected to a personal computer, and the computers are linked over a local area network. The traditional chalkboard is replaced by WYSIWIS interfaces among the workstations combined with a chalkboard-sized touch-sensitive screen located at the front of the meeting room.

WYSIWIS (pronounced "whizzy whiz") is a shorthand caption for "What You See Is What I See." This interface technology allows all meeting participants to see the same information on their displays. In addition, each person can point to displayed information with a telepointer that is made visible in real time to other participants. By
enabling collaborative manipulation of shared information, WYSIWIS can support the free-flowing contribution of ideas during brainstorming, plus organize various forms of visual data to aid decision-making. Computer technology is relied upon for manipulation, storage, and backup of displayed information. Knowledge media tools can also support retrieving information from databases, displaying information in alternative formats, and the importing of application programs to aid decision-making and planning activities, [27].

7.5.3 Workstations for Computer-aided Engineering

Klir [19] identifies at least three areas for computer-based design characterization studies:

1. Traditional, parametric modelling and simulation of system response.

2. Discovery of system characteristics.

3. Validation of postulated hypotheses.

The first area refers to the use of computer simulations to fine-tune system response by establishing optimal values for the governing design or process variables. Typically, the design problem can be stated mathematically and the computer is used to solve it automatically. In the domain of structural engineering, for example, there are numerous software packages available for automatic design of most structural members and floor slab systems.

System characterization studies use the computational capacity of the computer to experiment with the performance of an isolated subsystem or a complex, integrated system. For an isolated system, statistical or stochastic methods can be implemented to define the
sensitivity of its response with respect to each design or process variable. In the case of a complex system, potential interdependencies among the outputs of various disciplines can be identified and explored in terms of their impact on global performance and the Interface Index. Taguchi methods [24] are examples of experimentation techniques that lend themselves to computer implementation.

Lastly, the computer can be used to validate innovative solutions by combining features of the two preceding modes of operation. That is, computer studies can first be used to characterize the relationships between response and the vector of design variables so as to confirm whether a solution concept satisfies the Independence Axiom. If the Independence Axiom is satisfied, the computer can then be used to perform parametric design so as to maximize the amount of overlap between the system range and the functional requirements, thereby minimizing the information content (Information Axiom).

The DICE [25] project at M.I.T. is an example of a distributed workstation environment that can support computer-based design activities. DICE [25] is an object-orientated blackboard system for automated design. The blackboard system consists of a number of distributed knowledge sources and a central blackboard. The knowledge sources provide the domain knowledge necessary for the design process. The blackboard is a domain-independent framework. It controls the flow of the design process and stores the solution information developed by the knowledge sources. Thus, the blackboard maintains the status of the project and can be monitored by the project manager. The knowledge sources modify the blackboard, communicate through the blackboard, and follow the flow of control
established by the blackboard. The project's database can be embedded in a hypermedia system since DICE [25] stores data as objects and the nature of a particular piece of data, i.e., text, graphic, audio, or video, can be specified in a slot and attached to a method for executing data retrieval and presentation.

Consider the application of the DICE system [25] to performance-based design. Once the overall design matrix, including interfaces, is established and accepted by the project team, it can be used by the blackboard for controlling the flow of the design process. The blackboard can automatically prompt each knowledge source for design data in a sequence that maintains the independence of the functional requirements. For the selection and detailing of routine concepts, the distributed knowledge sources can be knowledge-based systems that assume the roles of design experts. Otherwise, a network of engineering workstations can be used. The individual knowledge sources can evaluate and optimize their design variables in the context of the current design data and notify the blackboard of their output. If design changes occur, the blackboard can use the structure of the design matrix to notify all affected knowledge sources of the change and the design process starts again.
7.6 References


Chapter 8 Summary and Conclusions

8.1 Summary

A framework for performance-based design has been proposed. It is a systems-based approach where the principles of Axiomatic Design are relied on to provide a scientific structure for the design process. The concepts of hierarchical decomposition and zig-zagging between design domains formalize the functional requirements at each level of abstraction. Following the creative synthesis of solution alternatives, the design equations \((FR)=[A](DV)\) and \((DV)=[B](PV)\) explicate the relationship between each alternative and the stated requirements. Lastly, the evaluation and selection of optimal solutions is performed through use of the Independence and Information Axioms.

The Independence Axiom is used to evaluate the quality of the mapping between requirements and solution alternatives. It stipulates that each functional requirement must be independently satisfied by a unique design variable. This independence condition ensures the advancement of solution concepts that are controllable and, hence, adaptable to changes in requirements. Once a set of solution alternatives that satisfy the Independence Axiom are established, the Information Axiom is used to identify the optimal solution by prescribing selection of the solution alternative with the lowest information content. In this context, information content is a quantitative measure of design complexity with regards to the probability of satisfying the specified functional requirements. According to the Information Axiom, the greater the uncertainty in obtaining satisfactory design capability or successful task execution, the greater the
amount of information associated with the solution and the greater the complexity.

A case study illustrating the application of Axiomatic Design to the design of a structural frame was presented in Chapter 2. This design example demonstrated the power of Axiomatic Design as a generic tool for organizing the solution process. In particular, the need to proportion the structural frame on the basis of allowable-deflection criteria prior to consideration of allowable-strength criteria was made apparent by application of the Independence Axiom to the governing design equation \( \{FR\} = [A]\{DV\} \). Such a stiffness-based approach, however, runs counter to the traditional, iterative, strength-based approach for design of rigid frames for low-rise buildings. Nevertheless, the validity of the axiomatic interpretation was substantiated by producing a frame design that is about one-half the weight of the solution obtained from convergence of the iterative, strength-based approach.

In addition to advancing the principles of Axiomatic Design, this thesis also proposed the concept of an Interface Index as an information-based measure of the complexity associated with the integration of building elements. Although design and construction planning of isolated subsystems and components may produce solutions that are optimal in the sense of the Independence and Information Axioms, subsequent integration of these individual elements into a total system can introduce explicit and/or implicit couplings between elements. Explicit couplings refer to different design disciplines making use of the same information or design variables. These are functional couplings and occur during the mapping of design requirements in the functional domain to
design variables in the physical domain. Implicit couplings, on the other hand, may be hidden from the designers because they occur during the mapping of the design variables in the physical domain to construction activities in the process domain. Implicit couplings reflect interfaces arising from the need to physically integrate subsystems and components. The proposed Interface Index is derived from graph theory, and it is similar to the family of complexity metrics that have been developed for evaluating the modularity of large-scale software systems. Its magnitude is a measure of the number of communication links that must be established between designers or construction tradesmen in order to coordinate the dependencies between coupled building elements.

Use of the proposed framework for performance-based design, including the design axioms and Interface Index, was demonstrated in Chapter 5 through application to a case study. Development of the case study involved systematic review and evaluation of a portion of the design and construction planning decisions associated with the delivery process for an actual building project: a four-story parking garage constructed of cast-in-place concrete with post-tensioned slabs. The following levels of abstraction were considered:

1. System design.
2. Subsystem design.
3. Component design.

At each level of abstraction, the concepts of functional decomposition, design axioms, and zig-zagging between design domains were used to construct a logical and robust mapping sequence from functional requirements to design variables to construction process variables. The
Independence Axiom aided in reasoning about multiple design requirements, extracting the pertinent pieces of information from the project data, and identifying the logic of the design and construction processes. Once the logic of the mapping between design domains was identified, the Information Axiom and the Interface Index were invoked as a means for quantifying design complexity in terms of both technical performance and interface issues. Specifically, the information content per the Information Axiom was used to quantify technical merit with regard to satisfying the functional requirements, and the Interface Index numerically defined the interface complexity due to couplings arising from the integration of subsystems and components into a total, constructed system.

The problems of where and how to improve the design and construction process for the parking garage case study were discussed in Chapter 6. For this task, the design axioms and Interface Index were interpreted as a framework for identifying targets for innovation. As a result, new solution concepts for the floor slab system and parapet/facade were advanced so as to satisfy the following targets for improved product and process designs:

1. Reduced intra-system coupling per the Independence Axiom.

2. Reduced inter-system coupling per the Interface Index.

3. Improved performance with new technology per the Information Axiom.

Lastly, a two-part strategy for implementing performance-based design on a widespread basis was outlined in Chapter 7. The first part of the strategy developed an
organization structure for the project team that seeks to minimize the coordination complexity among designers and contractors. The second part of the strategy discussed the use of the computer as an enabling technology for improving the information-processing capabilities of the project team.

The structure of the project team relies on a project manager to represent the interests of the client/owner and to provide a control center for integrating design and construction activities. If there is a design or construction problem, all affected requirements and design variables are brought to the attention of the project manager. A collaborative decision is made in the context of overall project performance, and the new requirements or design variables are input to the evolving design. This approach is similar to the integrative, problem-solving organization structure adopted by Boeing for introducing the 747 airplane in the mid-1960's.

The proposed system architecture for computer-based support consists of a hypermedia system as a project database, a knowledge media environment for facilitating collaborative, face-to-face meetings, and a distributed network of engineering workstations. These three elements were selected to satisfy the following set of functional requirements:

1. Capture project history.

2. Support collaboration among members of the project team.

3. Support the decision-making sequence, i.e., problem identification, synthesis, evaluation, and selection of solution alternatives.
8.2 Conclusions

The basic premise of this thesis is the development of a rational methodology for performance-based design of constructed facilities. In Chapter 1, the following research objectives were identified as a means for validating the proposed methodology:

1. Develop and implement the methodology within a specific problem application.

2. Demonstrate the capacity to evaluate design decisions and to quantify performance merit at various levels of design detail.

3. Identify and verify targets for redesign in order to improve quality.

The following conclusions can be drawn from the successful completion of the above research objectives:

1. The proposed framework provides a rational, descriptive methodology for performance-based design of constructed facilities. It is a formal strategy for identifying, expressing and dealing with multiple, global functional requirements, such as the need to provide parking for a number of vehicles; the need to provide for the safety of the parking garage's users; and the need to provide a number of years of service without excessive maintenance. The axiomatic approach reduces the complexity of trying to satisfy many, simultaneous objectives by decomposing each functional requirement into a cohesive network of sub-requirements for conceptual and detailed design. By externalizing the outputs of the decomposition and mapping activities, the design and construction variables that influence each functional requirement as well as the dependencies between
requirements can be identified throughout the project delivery process.

2. The Independence Axiom, Information Axiom, and the Interface Index can be used to reason about and quantify the relative merit of solution alternatives. In turn, the ability to quantify performance merit provides an objective basis for selecting optimal solutions. The design axioms and Interface Index are fundamental concepts that permit a homogeneous approach to design decision-making at all levels of abstraction. In addition, they also provide a strategy for identifying targets for innovation and for reasoning about the merit of proposed innovations.

3. Much of the complexity associated with the design and construction of constructed facilities is due to interface issues arising from the need to integrate isolated subsystems and components into a total system. The Interface Index provides a measure of interface complexity to aid in the generation and selection of solution alternatives that minimize interface complexity. The design equations \((FR) = [A](DV)\) and \((DV) = [B](PV)\) enable the identification and resolution of interface issues and task dependencies during the design and construction planning phases.

4. Advancement of performance-based design requires an integrated project team and enhanced capacity for information processing. The need for an integrated project team follows from item 3, above, concerning the impact of interface issues on complexity. Clearly, the resolution of interfaces between building elements requires a systems-orientated, multi-disciplinary approach so that the intent of each element with regard to
satisfying functional requirements is maintained, while new concepts and configurations are advanced. In addition, concurrent design and construction planning provides a structured framework for reasoning about constructibility as a performance requirement.

The complexity of the resulting design decisions is dependent upon realistic, quantitative expressions of system capability. This data is necessary to search for candidate solutions, evaluate alternatives, and select optimal solutions per the Information Axiom. In addition, project decisions must be documented to simplify any redesign efforts and to aid future projects. Therefore, advanced computer-based information systems must be available to members of the project team to support an exhaustive search for the best alternatives in a short period of time and to provide documentation for all project decisions.

8.3 Future Work

Figure 8-1 presents the author's vision for integrating the design and construction of facilities. The overall goal is the development of a strategy for total product realization that supports the concepts of improved project quality, reduced delivery times, and more efficient use of material and labor resources. The proposed project delivery process is based upon integrating three types of activities: system architecting, product development, and process development.

System architecting involves the identification of performance requirements (PRs) in the client domain, the abstraction of top-level FRs in the functional domain from the PRs, and the synthesis of a concept solution in the
physical domain. Product development is an expansion of the mapping between the functional and physical domains so as to refine or detail the concept solution. The product development group works with project-team members from both system architecting and process development to complete the FR and DV hierarchies through a combination of functional decomposition and zig-zagging activities. Process development involves the mapping of the DVs specified in the physical domain to process variables for controlling the manufacture and construction of the DVs. During product development and process development, the system architect coordinates the functional decomposition and zig-zagging activities in order to obtain concurrent design and construction. The system architect also focuses on the identification and resolution of interface issues so as to reduce project complexity.

Improved coordination and integration of design and construction activities requires a framework and a kit of design tools that enable a quick and efficient response to a wide-range of performance requirements. Thus, the centerpiece of Figure 8-1 is the notion of a design-support technology that contributes to effective problem-solving within the areas of system architecting, product development, and process development. As shown in Figure 8-2, design-support technology includes design methodologies; advanced CAE tools and information systems for helping system architects, product designers, and process designers synthesize optimal solutions per Axiomatic Design and the Interface Index; computer-simulated, virtual environments that allow rapid prototyping of solutions; and organizational strategies supporting integration of design and construction teams.

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FIGURE 8-2. DESIGN-SUPPORT TECHNOLOGY
Figure 8-2 depicts design-support technology as a merger of theoretical and applied knowledge, i.e., industry expertise. Research in the area of design theories and principles provides a basis for the development of robust methodologies supporting general practice. Clearly, advances in analytical methods would not have been possible without a strong foundation in the engineering sciences. The slope-deflection method and the finite element method, for example, are two of the most important contributions in the area of computerized structural analysis. Each is founded upon elements of basic structural theory: the slope-deflection equations are derived from the moment-area theorems and the finite element method is a numerical approximation for the theorem of virtual work. Therefore, it is only logical to assume that the development of structured and comprehensive paradigms for design should also rely on objective, scientific principles.

The role of industry is to supply the domain knowledge necessary for the design environment to be useful within a business enterprise. Researchers in the area of design theory typically are from universities, and they may be too far removed from current practice to understand the types of information that are needed for effective design and communication. In addition, industrial experience gained from the delivery of actual projects can provide valuable insights in the areas of organizational strategies, life-cycle cost models, and the management of innovative designs and construction processes.

This thesis has combined the following disciplines with domain knowledge in the area of parking structures to develop and demonstrate a framework for performance-based design of constructed facilities:
1. Axiomatic Design.
2. Information Theory.
4. Graph Theory.
5. Statistics.

The advancement of this framework as a valid design methodology requires additional illustrative examples to demonstrate its effectiveness and exploratory studies to establish the limits of its applicability. Interaction with industry provides one cornerstone for expanding the current database of system ranges to include requirements pertaining to cost and environmental demand as well as other problem domains, such as the design bridges, industrial facilities, and housing systems.

The delivery of large-scale, constructed systems is one area of study for developing an understanding of the limits of the current framework. The term 'large-scale' refers to the fact that these systems require the integration of a multitude of subsystems and components. Examples are regional transportation systems, water and wastewater treatment systems, and electric power stations. Without a theoretical framework for decision-making, the successful delivery of these projects must rely on the acquired expertise of construction management firms such as Bechtel, Stone & Webster, and Parsons. Thus, the research challenge is to determine whether fundamental principles can be abstracted so as to generalize, codify, and simplify the delivery process.

Consider the parking garage case study presented in Chapter 5. Interface issues made a significant contribution to overall design complexity at the level of component design and construction. It appears that the
individual designers perform better with respect to issues of technical merit than issues of system integration. That is, design decisions involving the need to satisfy functional requirements within isolated knowledge domains (such as, garage serviceability, the reliability and durability of the structural platform, and constructibility issues associated with cast-in-place concrete construction) have low information measures per the Information Axiom. However, there is an explosive growth in interface complexity per the Interface Index as the level of design detail increases. Ad hoc resolution of these interfaces through trial-and-error approaches, empiricism, and intuition can compromise project quality by negatively impacting global performance and/or increasing the length of the design and construction cycles.

For a large-scale system, the interface complexity can be exponentially larger than that for the parking garage. This means that much of the effort expended during the delivery process may be skewed to resolving the interface issues. Unless the interfaces are resolved during the design process, on-site expedience in the interest of construction costs and time may compromise project quality with regard to the functional requirements of the client/owner. Therefore, the ability to systematically study and evaluate the delivery process for large-scale, constructed systems can provide the client/owner with a rational framework for assessing the total quality of the completed project.

Work in the area of design theory is the second cornerstone for advancement of performance-based design as a design methodology. Further study of the design axioms is one research topic. By definition, axioms are
postulated as fundamental truths based on observing a large number of cases. They cannot be proven or derived, and axioms can only be refuted by counterexamples. Thus, the research challenge is to study more projects from the construction industry so as to develop a complete taxonomy of problems that test the universality of the Independence and Information Axioms. Such fundamental research could also explore the existence of additional axioms.

A second research topic in the area of design theory is to investigate the potential for incorporating other scientific approaches, such as Taguchi techniques and the morphological techniques advanced by Pahl and Beitz. Taguchi techniques involve the use of mathematical analyses to separate established designs into controllable and uncontrollable factors. Controllable factors are aspects of system response that can be easily adjusted and made to conform to desired requirements. Uncontrollable factors contain 'noise' that makes their response unpredictable. Therefore, Taguchi techniques can provide an analytical basis for determining design sensitivity and identifying the non-zero elements of the design matrix during the development of innovative components and configurations.

Morphological techniques aid the creative aspects of the design process by providing catalogs of known methods for carrying out fundamental functions, such as energy conversions, material conversions, signal conversions, and physical effects. The generation of solution concepts that must satisfy a variety of functions occurs through systematic synthesis of differing combinations of parts or elements. Although the catalog entries are based on scientific principles, the subsequent selection of the best solution concept relies on the ad hoc use of value
scales and weighting factors. The design axioms, on the other hand, provide a science base for evaluating the outputs of creative synthesis. Thus, a potential research avenue is to combine the morphological techniques with the design axioms in order to create a hybrid design environment that supports all aspects of the design process, i.e., problem identification, creative synthesis, and evaluation.
Appendix A  Optimum Combination of Material Properties for Strength-Based and Stiffness-Based Design

1. Bending Element

Bending elements are usually selected for the portion of the floor framing system that transmits the distributed gravity loads to the supporting columns, and this usage can represent a significant percentage of a structure's total weight. The peculiarity of the proposed parking system is the fact that the design of the floor framing also impacts the extent and subsequent cost of the subsurface excavation. The depth of excavation is dependent upon the structure's height so that a sufficient range of vertical motion can be provided. The height of the structure, in turn, is a function of the depth of the floor system elements and the specified clearance per floor. In order to prevent the selection of a lightweight material that requires relatively large member depths to satisfy strength and stiffness criteria, the material selection process for bending elements will treat member span-to-depth ratio (L/D) as a constant.

Consider a cantilever beam of span length \( L \) and depth \( D \) subjected to a transverse load \( P \) at its free end. The maximum bending moment occurs at the beam's fixed-end and is given by the product \( PL \). The corresponding maximum, elastic bending stress \( \sigma \) occurs at the extreme fibers of the beam's cross-section and is given by

\[
\sigma = \frac{PL}{S} \quad (A-1)
\]

where \( S \) refers to the beam's section modulus. For common structural shapes, such as rectangles, circles, and I-beams, \( S \) can be expressed as the product of the cross-
sectional area $A$, section depth $D$, and a proportionality constant $C_s$:

$$ S = C_s AD \quad (A-2) $$

The cross-sectional area of the section is a variable, and it can be expressed in terms of the mass of the beam $M = \rho AL$, or

$$ A = M/\rho L \quad (A-3) $$

where $\rho$ is the material density. Substitution of Equations (A-2) and (A-3) into Equation (A-1) yields

$$ \sigma = \rho \frac{PL^2}{C_s MD} \quad (A-4) $$

We can solve Equation (A-4) for the mass $M$ to give the governing least-weight optimization function:

$$ M = \frac{PL}{C_s} \frac{L}{D} \frac{(\rho/\sigma)} \quad (A-5) $$

Therefore, select the material with the minimum weight-to-strength ratio $\rho/\sigma$ in order to minimize the mass of the beam for an applied moment $PL$ and span-to-depth ratio $L/D$.

The formula for the elastic deflection $\delta$ of the beam is given by

$$ \delta = \frac{PL^3}{3EI} \quad (A-6) $$

where $E$ is the elastic modulus of the beam material and $I$ is the moment of inertia of the beam's cross-section.
Equation (A-6) also can be expressed as a function of the beam's cross-sectional area A and depth D:

\[ \delta = \frac{PL^3}{3C_I EAD^2} \quad (A-7) \]

where \( C_I \) is the proportionality constant \( I/AD^2 \).

Substitution of Equation (A-3) into Equation (A-7) and then solving for the beam's mass \( M \) yields

\[ M = \frac{L^2 P (L/D)^2 (\rho/E)}{3C_I \delta} \quad (A-8) \]

To minimize the beam's mass \( M \) for a required stiffness \( (P/\delta) \), select a material with the minimum weight-to-stiffness ratio \( \rho/E \).

2. Axial element

Consider a column of length \( L \) subjected to an axial load \( P \). Both its axial stress \( \sigma \) and axial extension \( \delta \) are inversely proportional to the column's cross-sectional area \( A \):

\[ \sigma = \frac{P}{A} \quad (A-9) \]

\[ \delta = \frac{PL}{AE} \quad (A-10) \]

where \( E \) is the elastic modulus of the column's material. Substituting Equation (A-3) into Equations (A-9) and (A-10) and then solving for the column's mass \( M \) yields two conditions for optimization.

\[ M = PL(\rho/\sigma) \quad (A-11) \]
\[ M = \frac{L^2 E}{\delta} \left(\frac{\rho}{E}\right) \]  \hspace{1cm} (A-12)

For strength-based design of the column, Equation (A-11) indicates that the mass is minimized by selecting the material with the minimum weight-to-strength ratio \( \rho/\sigma \). For stiffness-based design, the mass is minimized by selecting the material with the minimum weight-to-stiffness ratio \( \rho/E \) per Equation (A-12).
Appendix B  Probabilistic Evaluation of Traffic Flow Capacity

1. Mathematical Evaluation

The traffic flow capacity for a given functional design can be calculated on the basis of a level of service (LOS) approach, [1]. Use of LOS criteria in the design of parking structures is an extension of the LOS system developed by traffic engineers for classifying traffic flow conditions. The level of service designation for traffic conditions decreases from LOS A to LOS F as the amount of congestion increases. Level of service A corresponds to virtually free traffic flow and no delays; LOS F signifies gridlock conditions, [1].

For the design of parking structures, the acceptable LOS varies with respect to the intended user: employees versus short-term visitors. Employee parking conditions are characterized by concentrated rush periods in the morning and evening. On the other hand, facilities primarily devoted to visitor parking, such as car parks for shopping areas, must sustain high levels of arrival/departure activity during most hours of operation. Consequently, a better level of service is required for visitors than for employees. In fact, LOS A or LOS B is recommended for parking garages intended for short-term visitors, while LOS C or LOS D is recommended for employee parking, [1]. Therefore, this case study will assume LOS C to evaluate the flow capacity of the car park's functional layout.

The flow capacity is a function of the mean inhibiting period or travel time for each vehicle in the traffic stream during a peak hour, [1]. The mean inhibiting period is determined by the number of cars arriving and departing along a
particular circulation route plus the number of cars passing through the route on the way to other parking stalls and/or exits. The equation for calculating the mean inhibiting period $\Sigma t$ is as follows, [1]:

$$\Sigma t = p*t_p + u*t_u + s*t_s + e*t_e$$  \hspace{1cm} (B-1)

where: $\quad p =$ number of vehicles parking along the travel route.

$t_p =$ mean inhibiting period of 'p' vehicles.

$u =$ number of vehicles unparking and departing along the travel route.

$t_u =$ mean inhibiting period of 'u' vehicles.

$s =$ number of vehicles seeking a stall but parking off the travel route under study.

$t_s =$ mean inhibiting period of 's' vehicles.

$e =$ number of vehicles passing through the travel route from another area on the way to an exit.

$t_e =$ mean inhibiting period of 'e' vehicles.

Values for $t_p$ and $t_u$ are a function of the designated level of service and the geometry of the parking bays. For LOS C and the particular parking geometry specified, Reference 1 suggests that

$$t_p = 1/764 \text{ hours.} \hspace{1cm} (B-2a)$$

$$t_u = 1/716 \text{ hours.} \hspace{1cm} (B-2b)$$

Reference 1 also establishes the following standard values for $t_s$, $t_e$, and $\Sigma t$:  

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\[ t_s = \frac{1}{1500} \text{ hours.} \]  \hspace{1cm} (B-3a)

\[ t_e = \frac{1}{1800} \text{ hours.} \]  \hspace{1cm} (B-3b)

\[ \Sigma t = 0.68 \text{ hours for LOS C.} \]  \hspace{1cm} (B-3c)

Substitution of Equations (B-2a,b) and (B-3a,b,c) into Equation (B-1) yields a multi-variable expression in terms of the vehicle quantities \((p,u,s,e)\). To completely fill or empty the car park, the static capacity \(N\) must be given by the sum \((p+u+s+e)\). As a result, Equation (B-1) can be reduced to one equation with one unknown by apportioning a percentage of the total capacity \(N\) to each type of vehicle traffic: \(p,u,s,\) and \(e\).

\[ \Sigma t = (\alpha_p t_p + \alpha_u t_u + \alpha_s t_s + \alpha_e t_e) N \]  \hspace{1cm} (B-4)

where:

- \(\alpha_p\): percentage of vehicles parking along the travel route.
- \(t_p\): mean inhibiting period of \(\alpha_p\).
- \(\alpha_u\): percentage of vehicles unparking and departing along the travel route.
- \(t_u\): mean inhibiting period of \(\alpha_u\).
- \(\alpha_s\): percentage of vehicles seeking a stall but parking off the travel route under study.
- \(t_s\): mean inhibiting period of \(\alpha_s\).
- \(\alpha_e\): percentage of vehicles passing through the travel route from another area on the way to an exit.
- \(t_e\): mean inhibiting period of \(\alpha_e\).

A characteristic range of values for capacity \(N\) can be generated by considering how the specified parking spaces are
distributed about the facility and a variety of scenarios for traffic flow. For example, about 60% of the parking spaces are located along the sloped floors and driving corridors that provide access to each parking level. In addition, the peak morning arrivals and peak evening departures for office usage are typically equal to 40-70% of capacity and are typically opposed by a traffic flow equal to 5-15% of capacity, [1]. The resulting lower bound capacity is about 720 cars and the upper bound capacity is about 1320 cars. Consistent with the concept of maximum entropy [2], these two limits can be used to define a uniform probability distribution of values so as to maximize the uncertainty of the analysis. The relationship between the calculated system capacity and the desired capacity is shown in Figure 5-5.

2. References


Appendix C  Probabilistic Evaluation of Concrete Service Life

1. Introduction

The purpose of this appendix is to provide justification for the probabilistic service life distribution discussed in Subsection 5.4.1 and presented in Figure 5-24. The service life distribution reflects the probability of failure of the concrete due to chloride-induced corrosion of the reinforcing steel. This can be a critical problem because corrosion of the steel negatively impacts concrete performance in the following ways.

1. The formation of rust increases the volume of the steel, thereby introducing expansive forces within the concrete matrix. These forces are capable of cracking and spalling the concrete resulting in a loss of cross-section.

2. If corrosion is allowed to proceed, serious structural weakening can occur due to extensive loss of the steel/concrete bond and reduction of the effective steel area for load capacity.

Concrete is a porous material that allows the penetration of both the oxygen and water that is necessary for rusting to occur. However, widespread rusting of reinforcing steel is not evident in most applications because the concrete matrix naturally provides both physical and chemical protection to the embedded steel. Concrete can offer an effective physical barrier through design of the concrete mix and control of the in-situ placement and curing processes in order to reduce permeability. The high alkalinity of concrete (pH in range 12-14) provides a chemical barrier to steel corrosion by contributing to the formation of a protective, passivating oxide layer around the embedded steel, [5,15]. In addition, the high pH values greatly limit the system's ability to
sustain the electrochemical reactions necessary for rusting to occur.

Despite the above-cited barriers to corrosion, concrete bridges and parking structures damaged by corroded reinforcement are a recognized problem. One contributing factor is the ingress of corrosion activating agents into the concrete matrix. In recent years, for example, much attention has been focused on the deteriorating condition of highway bridges subjected to the repeated use of de-icing salts. It is now known that chloride ions are capable of changing the embedded steel from a passive state to an active corrosion state. In the case of open car parks, de-icing salts can be deposited on the parking deck by automobiles and by human volition.

The corrosion process for reinforcing steel is separable into two stages: initiation and propagation. Destruction of the passivating oxide layer occurs during the initiation stage. The subsequent propagation stage is marked by electrochemical reactions involving the transfer of electrons and the formation of ferrous hydroxide (rust). Once penetration of the oxide layer takes place, the rate of corrosion is made uncertain by its complex dependence on the electrical resistance of the concrete and the amounts of moisture and oxygen that are available to sustain the metallic conversion. As a result of this uncertainty, the duration of the propagation stage can be treated as a factor of safety for purposes of design, [4]. Therefore, calculation of the service life distribution is based on the time necessary for corrosion initiation.
2. Diffusion and Reaction of Chloride Ions in Concrete

The process of chloride ion ingress into the concrete matrix is governed by Fickian diffusion, [4,5,13,15,17]. According to Fick's law, the rate of chloride ion transfer through a differential element can be expressed by the following equation, [6].

\[
\frac{dn}{dt} = -DA \frac{C_1 - C_2}{\Delta x} \quad (C-1)
\]

where:  
- \( n \) = quantity of chloride diffusing.  
- \( D \) = diffusion coefficient.  
- \( A \) = cross-sectional area normal to diffusion flow.  
- \( C_1 \) = chloride ion concentration at surface.  
- \( C_2 \) = chloride ion concentration at depth of penetration.  
- \( x \) = penetration distance.  
- \( t \) = time.

All of the chloride ions that diffuse into the concrete matrix are not free to initiate corrosion. The diffusion process also involves a chemical reaction between the penetrating ions and the concrete matrix, [15,17]. The incoming ions are chemically bound with hydrated tricalcium sulfoaluminate compounds already present in the cured concrete. These reactions neutralize the chloride ions by producing tricalcium chloroaluminate. In fact, about 75% to 90% of the chloride concentration per weight of concrete is neutralized, [17]. As a result, the binding capacity of the concrete matrix determines the total amount of chloride necessary for incipient initiation of corrosion.
\[ dn = a \ A \ dx \]  \hspace{1cm} (C-2) \\

where: \( a = \) required amount of chloride per unit volume needed to bind with hydrated tricalcium sulfoaluminate in concrete matrix.

A \( dx = \) volume of differential element.

Substitution of Equation (C-2) into Equation (C-1) and separation of variables yields:

\[ x \, dx = -\frac{C_1 - C_2}{a} \, dt \]  \hspace{1cm} (C-3) \\

An expression for calculating the time required for the virtual arrival of chloride ions at any distance \( x \) from the surface can be determined by integrating Equation (C-3) and assuming that the chloride ion concentration \( C_2 \) is equal to zero at the point of interest.

\[ t = \frac{x^2 \ a}{2 \ D \ C_1} \]  \hspace{1cm} (C-4) \\

Equation (C-4) indicates that the time to corrosion initiation is proportional to the square of the distance between the concrete surface and the reinforcing steel, \( t = k \, x^2 \). The proportionality constant increases with the concrete's binding capacity \( a \). Thus, the tendency of the chloride ions to bind with tricalcium sulfoaluminate retards diffusion and corrosion initiation. Although this simple
diffusion/reaction model does not include the effects of time-dependent changes in the diffusion coefficient $D$ and cyclic wetting and drying, it is consistent with design equations presented in the literature [4,13,15]. Reference [1], for instance, suggests that the use of the simple diffusion law appears reasonable on the basis of comparison with chloride measurements on over 40 existing structures.

3. Decisive Parameters

Based on Equation (C-4), four parameters must be evaluated in order to calculate an estimated service life: binding capacity $a$, surface chloride concentration $C_t$, coefficient of diffusion $D$, and depth of reinforcing steel $x$. The purpose of this section is to provide rational values for each of the four critical parameters.

**Binding capacity $a$.** The binding capacity $a$ is dependent upon cement type. Since it refers to the amount of tricalcium sulfoaluminate present in the concrete matrix, it is equal to the amount of tricalcium aluminate ($C_3A$) contained in the base cement. For ordinary portland cement, the $C_3A$ content is in the range of 10%-15% by weight of concrete, [14].

**Surface chloride concentration $C_t$.** Unfortunately, little published data is available on chloride ion concentration for the exposed surfaces of actual structures. Most research in the area of chloride-initiated corrosion has focused on detailed characterization of the diffusion and corrosion processes, rather than comparative study of existing systems. However, highway bridge deck data presented in Reference [6] suggests a surface concentration of 1.0%-1.5% by weight of concrete.

At first glance, chloride concentration data gathered from
highway bridges may appear too severe for use in the design of parking garages. But it is important to note that large deposits of de-icing salts on the bridge deck tend to occur at discontinuities, such as cracks and along the curb. For most portions of the bridge surface, the buildup of applied de-icing salts is tempered by runoff, automobile traffic, and diffusion.

The surface concentration of chlorides in parking structures, on the other hand, is strongly dependent on de-icing salts deposited by vehicles and would tend to be maximized within the individual parking stalls. As a result, the surface concentration values collected from highway bridge decks are considered peak values of chloride ion concentration for analysis of the parking garage. Thus, the chloride concentration $C_i$ at the concrete surface is assumed to vary over the range 1.0%-1.5% by weight of concrete.

The remaining parameters of Equation (C-4) are the diffusion coefficient $D$ and the depth of the reinforcing steel. Input values for these parameters are a function of the design variables specified during design of the concrete mix and component details. Thesis subsection 5.4.1 indicates that the structural engineer used the following design variables to control the design against chloride-initiated corrosion:

1. Water-to-cement ratio w/c for concrete mix design.
2. Silica fume admixture to concrete mix.
3. Clear concrete cover over reinforcing steel.
4. Epoxy-coated reinforcing steel.

The diffusion coefficient governing the ingress of chloride ions into the concrete matrix is a function of both the specified water-to-cement ratio and the amount of microsilica admixture. The water-to-cement ratio determines the
potential porosity of the concrete matrix and the permeability to the inflow of chloride ions, [1,4,13,14]. Concrete of low permeability requires the use of low values (less than about 0.45 [1]) for w/c. The silica fume admixture also reduces concrete permeability by filling pores through pozzolanic reaction and by physically blocking pores, [3,8,9,10,11].

Even for low permeability concrete, however, the potential exists for chloride-initiated corrosion of the reinforcing steel. In particular, variations in chloride ion concentration arising from deviations in mix design can introduce a concentration gradient along the length of the rebars capable of accelerating the corrosion process. Specifying epoxy-coating reinforcing steel provides a protective, physical barrier to chloride attack of the steel surface and offers a unique design variable for controlling corrosion within certain tolerances. Therefore, the diffusion coefficient D for use in Equation (C-4) must be a composite value reflecting the contributions of w/c, silica fume admixture, and the rebar coating.

One approach is to view the concrete matrix and epoxy coating as a multi-layered medium. For a composite medium consisting of n layers with thicknesses \(l_1, l_2, \ldots, l_n\) and diffusion coefficients \(D_1, D_2, \ldots, D_n\), the drop in concentration across the total thickness is given by the sum of the drops across each layer, [6]. Thus, the total diffusion resistance is equal to the series sum of the individual resistances \(l_i/D_i\).

\[
\frac{l_1 + l_2 + \ldots + l_n}{D} = \frac{l_1}{D_1} + \frac{l_2}{D_2} + \ldots + \frac{l_n}{D_n} \quad (C-5)
\]
Since the silica fume is distributed throughout the cement paste, the composite medium can be characterized by two distinct layers: a layer of concrete enhanced by silica fume admixture and an epoxy coating on the reinforcing steel. This simplifies Equation (C-5) to provide an expression for the effective diffusion coefficient of a composite, two-layered medium.

\[
D = (I_1 + I_2) \frac{D_1 D_2}{D_1 I_2 + D_2 I_1} \tag{C-6}
\]

Substitution of Equation (C-6) into Equation (C-4) yields a modified equation for concrete service life with respect to chloride-initiated corrosion where the depth \( x \) from the concrete surface to the reinforcing steel is replaced by the simple sum of the thicknesses \( I_1 \) and \( I_2 \).

\[
t = \frac{1}{2} \frac{I_1 + I_2}{D_1 D_2} \left( \frac{a}{C_1} \right) \frac{D_1 I_2 + D_2 I_1}{C_1} \tag{C-7}
\]

where:

\[D_1=\text{composite chloride diffusion coefficient for concrete enhanced with silica fume admixture.}\]

\[D_2=\text{chloride diffusion coefficient for epoxy coating on reinforcing steel.}\]

\[I_1=\text{specified depth of clear concrete cover.}\]

\[I_2=\text{thickness of epoxy coating.}\]

\[a=\text{binding capacity of concrete matrix.}\]
\[ C_1 = \text{chloride ion concentration at concrete surface.} \]

Project documents for concrete mix design specify a maximum water-to-cement ratio of 0.40 and a silica fume admixture of about 5% by weight of cement. Least-squares analysis of independent, published test data [12] compiled for an equivalent concrete mix design yields an effective diffusion coefficient \((D_1)\) of about 1.30 in\(^2\)/yr. (2.30 mm\(^2\)/day). In addition, the concrete cover \((l_0)\) is specified to be 1 1/2-inches with a placement tolerance of (+/-) 1/4-inches.

Thickness and chloride permeability requirements for epoxy coatings applied to reinforcing steel are outlined in Specification ASTM A 775 [2]. According to A 775, the thickness of the epoxy coating \((l_2)\) shall be in the range of 5 to 12 mils inclusive. Consistent with the permissible variation in coating thickness, the maximum diffusion coefficient \((D_2)\) for transfer of chloride ions is in the range of 1.05e-4 to 2.52e-4 in\(^2\)/yr.

4. **Probabilistic Service Life Distribution**

Equation (C-7) provides a comprehensive expression for calculating concrete service life due to chloride-initiated corrosion of the reinforcing steel. A summary of the stochastic properties of all the variables that appear in Equation (C-7) is given in Table C-1. The tabulated data for each variable includes the characteristic range of values, the type of random distribution, the mean value, and the standard deviation. All variables are assumed to converge to normal distributions for large sample populations. In addition, tabulated values for the mean and standard deviations of all variables except \(D_2\) are based on the convention that the characteristic ranges are within two
### TABLE C-1. STOCHASTIC PROPERTIES OF PARAMETERS GOVERNING CONCRETE SERVICE LIFE

<table>
<thead>
<tr>
<th>Description</th>
<th>Type of Distribution</th>
<th>Mean Value</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_1$</td>
<td>Normal</td>
<td>1.30 in$^2$/yr</td>
<td>0.65</td>
</tr>
<tr>
<td>$D_2$</td>
<td>Normal</td>
<td>0.000179 in$^2$/yr</td>
<td>0.0000368</td>
</tr>
<tr>
<td>$l_1$</td>
<td>Normal</td>
<td>1.50 in.</td>
<td>0.125</td>
</tr>
<tr>
<td>$l_2$</td>
<td>Normal</td>
<td>0.0085 in.</td>
<td>0.00175</td>
</tr>
<tr>
<td>$C_1$</td>
<td>Normal</td>
<td>1.25 $%$/weight</td>
<td>0.125</td>
</tr>
<tr>
<td>$a$</td>
<td>Normal</td>
<td>12.5 $%$/weight</td>
<td>1.25</td>
</tr>
</tbody>
</table>
standard deviations from the mean, i.e., 97.7% probability of occurrence. The standard deviation for the diffusion coefficient for the epoxy coating $D_2$ is assumed to be one-half of the mean in order to account for large variations in performance due to damaged or defective coatings. The properties of the resulting probability distribution for concrete service life are approximated through use of the First Order/Second Moment method, [7,16]. This statistical approach uses the mean and standard deviation of each stochastic variable to estimate the mean and standard deviation of the target distribution. The results define a normal distribution with the following properties:

1. Mean= 367 years.
2. Standard Deviation= 121 years.

Based on the above values for mean and standard deviation, a 50-year service life has about a 99.8% probability of success and an information content of virtually 0.0 bits.
5. References

1. ACI Committee 201, "Guide to Durable Concrete," ACI Committee Report 201, Detroit: American Concrete Institute.


