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A Formal Approach To Automating Conceptual Structural Design[1]

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Abstract

In the conceptual phase of structural design, a designer develops and investigates many potential alternatives for safe and economic transfer of loads that are to be carried by the structure. A methodology for automating conceptual structural design and an application of the methodology to a specific problem are presented in this report. Some of the salient aspects of the methodology are: (i) an explicit representation of the structural form, function, and behavior; (ii) modeling the structural engineering domain as well as the strategy employed by expert designers; (iii) using $Cost/Value$ ratio as an intrinsic measure of the merit of a design alternative; and (iv) reduced reliance on heuristics with more emphasis on first principles and fundamental knowledge. The categories of knowledge that need to be represented in a computer system to support the reasoning for conceptual structural design are identified. The use of such knowledge is illustrated through examples based on several different types of structures. A constraint classification system (to organize the constraints that arise from structural and exogenous considerations) is also proposed.

The abovementioned methodology is applied in the context of the problem of floor framing generation for steel office buildings. Floor framing generation involves providing a path to transfer the gravity loads incident upon the structure from their points of origin to the ground. This is achieved by placing various structural elements in an architectural plan, while meeting the requirements imposed by other entities (such as the architect, the mechanical engineer, and the contractor) involved in the design/construct process. We describe the knowledge and the reasoning behind a computer system, FFG (for Floor Framing Generator), which generates floor framing schemes for steel office buildings that are rectangular in plan and have a single service core. Constraints arising from structural as well as exogenous considerations are enumerated and their effects on the framing schemes are identified. We also elaborate on the evaluation mechanism for ranking alternative schemes, in addition to providing details of the computer implementation.

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Contents

Chapter 1

Methodology

The field of structural engineering has come a long way since Galileo first systematically studied the strength of materials and behavior of cantilever beams. Since the publication of Galileo's *Two New Sciences* over 350 years ago, major advancements have been made in the areas of structural analysis and design. With the advent of computers, significant research effort has been directed towards automating analysis and design of structures. Computer-aided structural design, in particular, has received considerable attention in the last decade.

The conceptual design of structures, wherein the designer investigates many potential alternatives and makes fundamental choices that have major impact on the downstream decisions, is one of the important areas for investigation from the standpoint of automation. Several works in this direction have been undertaken recently or are currently underway (e.g., [1,2,3,4,5,6,7,8,9]). It is generally recognized that heuristics play an important role in the creative process of conceptual structural design. Another characteristic of conceptual design, arising from economic considerations, is that typically several feasible design solutions are developed and evaluated.

The two primary forms of representation of knowledge in conceptual design systems are *procedural* and *declarative*. With its virtues of extensibility and versatility, there seems to have evolved a consensus amongst researchers in favor of declarative representation for developing computer aids for structural design. However, no consensus on a global framework for these systems has emerged. In this report we attempt to paint the "big picture" by describing a formal approach to automating the conceptual phase of structural design. We expound on the reasoning aspects of a conceptual design system in this chapter. The concepts discussed in here are illustrated through an example implementation in Chapter 2.

This chapter is organized in the following manner: a few definitions and background to this work are presented in the next section. The following section gives an overview of the methodology, and the subsequent sections consider the individual components of the methodology in detail. Conclusions are drawn in the final section.

It should be noted that the methodology discussed in this chapter is not tied to any particular knowledge representation formalism as long as the formalism is declarative in nature. Thus any scheme—rule-based, frames, predicate calculus, just to name a few—can be employed to implement the methodology.

1.1 Background

Musen [10] states that developing a knowledge system for performing an engineering task is, in many respects, analogous to developing a scientific theory; one must identify the underlying knowledge that defines the characteristics of the physical system being reasoned about, and one must also theorize the problem-solving approach of a given class of professionals in the domain of interest. Model-based reasoning has recently emerged as a useful paradigm for solving problems in diverse application areas [11,12]. In order to reason about a system in this approach, one represents the *form*, *function*, and *behavior* of the system being modeled explicitly, imparting flexibility and depth to the computer system.

The following definitions, adapted from Ref. [13], define the terms *form*, *function*, and *behavior* as seen from the perspective of structural engineering.

- *Form*: The form in the context of structures refers to the description of spatial arrangement of functional objects (such as beams, columns, etc.) and the physical attributes of such objects.
- *Function*: This refers to a qualitative description of the purpose of a structural system or an element. The primary purpose of the structure is to transfer the incident loads, as well as its self-weight, from their respective points of origin to the ground.
- *Behavior*: Behavior refers to the response of a structure to applied loads. Thus behavior is essentially the manifestation of the structural system performing its function—as a result of carrying loads the structure deflects and develops internal stresses.

Engineering design involves determining the *form* of a physical system, given its function and desired behavior, such that the system satisfies the constraints imposed on it. Analysis on the other hand involves determining a system's *behavior* given its form and function.

Structures are usually 'one-of-a-kind' systems. As a result, testing of physical models to determine the suitability of the design solution is generally not feasible (though it can be applied, for instance, in the case of wind tunnel model testing of high-rise buildings). However, because of human safety and serviceability considerations, it is necessary to develop reliable means to predict the behavior of the structure. Impracticality of the physical models, coupled with the need for behavior prediction, necessitates mathematical modeling (numeric as well as symbolic) of the structural response in terms of known quantities. In the case of design problems, to determine the form efficiently one also needs to model the problem-solving approach of the experts in the domain.

Different types of models—ranging from diagrammatic to physical—can be used to represent an engineering system. The representation of the form, function, and behavior of the engineering system can be used in conjunction with the representation of meta-level problem-solving knowledge, forming a layered reasoning system modeling two distinct conceptual entities: (a) the physical system, and (b) the human being reasoning about the physical system. To define the architecture of a computer implementation of these models, one should clearly identify the various components involved and establish the roles of the components in the overall scheme.

With this background, we can proceed to propose a methodology for developing knowledge systems to assist in conceptual design of structures. However, before moving on to such a description, we want to briefly mention another work in progress in a different design discipline, which is interesting because of certain similarities in its approach and outlook. The work being pursued envisions development of a computer-robotic system, *Designworld*, to assist in the production of small-scale electromechanical devices, such as disk drives, compact disc players, and robots [14].

For reasoning, Designworld will work from a declarative representation of fundamental knowledge in the relevant design disciplines to achieve high performance while avoiding the brittleness often encountered in traditional expert systems. One of the key concepts in the project is contemplation of a central database that will include product-specific information (such as manufacturing records, specifications, assembly plans, etc.) and product-general information (such as basic scientific and technological principles in electrical and mechanical engineering, details of the machinery available for manufacture and maintenance, etc.). As the reader will notice later, this concept corresponds well with three important components of our methodology—namely, *Structural Elements and Systems Knowledge*, *Behavior and Performance Knowledge*, and *Product Knowledge*—discussed in Section 1.

1.2 Overview of the Methodology

In the methodology for performing conceptual structural design in an automated environment presented here, we first identify different items of knowledge that are relevant to the design process, organize this knowledge into distinct categories (described below), reason from such knowledge to develop alternative solutions for a design problem, and finally evaluate and critique the generated alternatives. An overview of the different facets of the methodology is presented in the remainder of this section.

1. *Structural Elements and Systems Knowledge*: This is one of the basic categories of knowledge, containing information about the attributes like function, qualitative behavior modes, and form of generic structural elements and the systems that can be synthesized from them. The attributes will usually have a value (or a set of values) that will always be true. Some examples of structural elements are *Beam*, *Wall*, and *Cable*. The synthesized systems can be *Truss*, *Grid*, *Moment Resisting Frame*, etc. To illustrate, the function of an *Arch* is to carry the loads across horizontal spans through the primary behavior mode of compression and secondary behavior modes of bending and shear. The form can vary; some possible forms are, parabolic, radial, and funicular.

2. *Behavior and Performance Knowledge*: The behavior knowledge refers to the fundamental principles of structural engineering which quantitatively describe the forces, stresses, deflections, etc., for structural elements and systems mentioned earlier. An illustrative example of knowledge in this category is the set of equations expressing the distribution of shear and bending stresses across the cross-section of flexural members. General cable theorem, which relates the horizontal component of the cable tension with the geometry and external vertical loading on the cable, is another such example.

   Performance knowledge, on the other hand, refers to the knowledge about performance criteria imposed on the structure. Much of the knowledge contained in design standards and specifications is of this type. Design specifications are a source of statutory constraints that must be met by the final solution. Note that performance knowledge also encompasses knowledge about material properties. One sample usage of performance knowledge is the determination of the amount of individual loads and the load combinations that a structure must be designed for. Another example pertains to the control of wind induced vibrations in long-span bridges.

3. *Product Knowledge*: Knowledge about specific products that can be used for construction is classified under this category. Such knowledge may range from geometrical properties of commercially available hot-rolled steel sections to market knowledge about the availability of certain products in a particular region and the associated cost data.

4. *Concepts*: Various abstractions, e.g., architectural and structural patterns in the floor plan of a building, *Cost/Value* ratio, etc., play a supporting function in formulating strategy and defining evaluation criteria. Such abstractions are collectively denoted by the term *Concepts*.

5. *Strategy*: While a large fraction of the generic domain knowledge is contained in the modules *Structural Elements and Systems Knowledge*, *Behavior and Performance Knowledge*, and *Product Knowledge*, such base-level knowledge alone is not sufficient for solving a design problem. To efficiently generate design solutions, one must also capture meta-level knowledge, or problem-solving knowledge, that operates on the base-level statements and specifies how to utilize them. This aspect of the methodology models the approach of a set of professionals to the application task, as mentioned in Section 1.1. Thus, *Strategy* is meant to emulate the human thought process and to perform decision making based on experts' technique(s) of approaching the problem.

6. *Reasoning with Constraints*: Conceptual structural design can be performed by formulating, propagating, and satisfying constraints based on the knowledge contained in the modules described above. By (a) formulating constraints based on the project context as well as project-independent information, (b) propagating the effects of a constraint originating in structural engineering or exogenous domains to the same or other domains, and (c) selecting the values of attributes so that the constraints are satisfied, one can synthesize alternative structural schemes that can serve as candidates for evaluation and feedback.

7. *Evaluation and Feedback*: Usually, for a given design problem, there are more than one feasible candidate solutions that meet all the constraints, thus necessitating some evaluation mechanism. Evaluation may be based on an explicit or implicit consideration of the *Cost/Value* ratio [15,13]. A well-defined evaluation criterion, or a set of criteria, is a requisite constituent of a design methodology. Evaluation can also lead to feedback on the advantageous and disadvantageous aspects of different alternatives, and suggestions on improving an alternative.

Each of these components is described in detail in the following sections and their usage is illustrated with suitable examples.

1.3 Structural Elements and Systems Knowledge

As mentioned in Section 1.2, this component contains knowledge about various types of elements and systems that can be used for structural design. In terms of the type of knowledge being represented, the emphasis is on first principles of structural engineering and not heuristics. Thus, while knowledge of the form "a post-and-beam frame is unstable" will be included here, a statement similar to "a framed tube system is good only for buildings over 30 stories" will not be.

In the remainder of this section, we give some illustrative examples and show how reasoning based on *function* can be used to deduce the requirement for some structural components. We should reiterate that any declarative formalism can be employed for representing this knowledge. For instance, the knowledge below can be represented in terms of objects such as `Hanger`, `Floor Plate`, etc. having attributes *Function*, *Form*, and so on. Alternatively, it can equivalently be stated by means of first-order predicate calculus statements where, for example, *Form* is a relation that holds true between the objects `Floor Plate` and *2D-Horizontal*.

Hanger

Function	To transfer the applied loading in a vertical direction.
Primary Behavior	Axial Tension
Other Behaviors	None
Form	1D Vertical
Possible Materials	Steel, Wood
Supported By	Hanger, Transfer Girder, Wall Bracket

Floor Plate

Function	To collect vertical loads distributed in a horizontal plane and to provide a surface forming element.
Primary Behavior	Flexure
Other Behaviors	Shear
Form	2D Horizontal
Possible Materials	Reinforced Concrete, Steel Deck, Composite Deck, Plywood
Supported By	Beam, Column, Wall

Framed Tube

Function	To resist lateral loads.
Primary Behavior	Overturning moment resistance through axial forces in columns in the direction of the loads as well as the ones perpendicular; story shear resistance through bending in columns.
Other Behaviors	Shear Lag
Form	3D Vertical
Possible Materials	Steel, Reinforced Concrete
Supported By	Foundation

It should be noted that the above classification is based upon functional objects. In the representation based on function, we form instantiations from these objects to represent the actual physical entities. Thus, from a functional object like `Column`, we can form instantiations to represent `Column 1`, `Column 2`, and so on. Note, however, that there doesn't have to be a one-to-one mapping from physical objects to functional objects; the same physical object may perform more than one function. To illustrate, consider the case of structural design of a building. The *Structural Elements and Systems Knowledge* module will contain descriptions of `Floor Plate` (a member of the gravity load resisting system) and `Diaphragm` (a member of the lateral load resisting system), besides others. If the same physical entity performs the functions of both the `Floor Plate` as well as the `Diaphragm`, instantiation from both of them will result in the same object when the design solution is being synthesized. As we argue later, reasoning based on function results in greater flexibility and is more conducive to innovation.

To show how the above knowledge can be used, let us again consider the case of structural design of a building. From the fact that the structure is a building, we can infer that there will exist vertical loads (in addition to other types of loads) which will be distributed in a horizontal plane. This reasoning suggests that a structural element that can perform the function of collecting distributed vertical loads in a plane, will be needed. Looking at our knowledge base, we see that a floor plate can perform such a function and thus is a candidate element to be used in the structural system. If no other element can perform the said function, a floor plate has to be used, thus establishing a definite requirement of floor plate in case of a building. However, if the structure was a transmission tower, there is no function of collecting distributed vertical loads, thus making a floor plate unnecessary.

1.4 Behavior and Performance Knowledge

Behavior knowledge embodies the relationships between numerical quantities like loads, stresses, and deflections. Behavior knowledge is primarily first principle knowledge. For instance, the equation

$$f = \frac{Mc}{I} \tag{1.1}$$

expresses the relationship between the bending moment, M, bending stress, f, moment of inertia, I, and the distance from the neutral axis, c, for a structural element under flexure within the elastic limit. Some other examples of behavior knowledge in the case of a simply-supported beam under uniformly distributed load, w, are given below (where the symbols denote their usual meanings).

$$M = \frac{wl^2}{8} \tag{1.2}$$

$$\delta = \frac{5wl^4}{384EI} \tag{1.3}$$

A related type of knowledge, namely performance knowledge, specifies the legally required constraints on the behavior of the structure or its individual components. For instance, in the case of beams, there is commonly a restriction of the following form on the permissible deflection:

$$\delta \leq \frac{l}{\alpha} \tag{1.4}$$

where l is the span of the beam and α is some numeric constant, such as 240 or 360.

With the help of Eqs. (1.1)–(1.4), we can illustrate how behavior and performance knowledge can be combined during the process of conceptual design. Consider, for example, a steel beam with an I-section. We need to consider only the deflection due to live loads when satisfying Eq. (1.4). Let r denote the fraction of the total load that is due to live load. Replacing w by rw in Eq. (1.3) and combining it with Eq. (1.4), we get

$$\frac{5rwl^4}{384EI} \leq \frac{l}{\alpha} \tag{1.5}$$

Based on Eqs. (1.1), (1.2), and (1.5), and the relation $c = d/2$ (where d is the depth of the beam), we can deduce the general relationship for the minimum depth of a beam in terms of average allowable stress, f, the span, l, and the factor α.

$$d \geq \frac{5rf\alpha l}{24E} \tag{1.6}$$

When designing a specific beam, the values of r, l, E, and α will be known and an estimate can be made for f. Thus the depth can be selected in such a fashion that deflection requirements are not violated. To illustrate, consider the case of an A36 beam for which $E = 29000$ ksi, $\alpha = 360$ (to achieve a deflection limitation of $l/360$), $r = 0.6$ (corresponding to a 60% contribution of live load to total load) and allowable stress, $f = 24$ ksi (for A36 steel). Substituting these values, we get

$$d \geq 0.0372\, l. \tag{1.7}$$

Adjusting the equation to get d in inches while l is in feet, we get

$$d \geq 0.45\, l. \tag{1.8}$$

If the beam depth is selected in accordance with this criterion, then the code specified live load deflection limitation of $l/360$ is always satisfied for the illustrated case. This bit of knowledge is sometimes coded as a heuristic in structural design systems, but as the above example illustrates, it is unnecessary to do so in view of the ability to derive the relationship between d and l based on behavior and performance knowledge. Moreover, the relationship is more general and can be applicable in a wider variety of contexts (e.g., for different values of α or f) than the corresponding heuristic which will hold true only for some combinations of variables.

Performance knowledge is often based on past observations about the behavior, and thus the distinction between behavior and performance knowledge is sometimes blurred. For instance, the stress-strain relationship for common construction materials like steel and concrete can be determined experimentally, thus providing the behavioral basis; however, an idealized relationship contained in the specifications can be used when actually designing the elements, thus using constraints derived from performance knowledge. Because of the link between them, and because design codes contain both types of knowledge, we have chosen to put behavior and performance knowledge together in a single component.

1.5 Product Knowledge

The knowledge about the attributes of the products that can be employed for constructing a facility can be used to formulate constraints regarding the set of possible solutions, and to evaluate those solutions. This component of the methodology contains such knowledge including, for instance, the AISC table of steel shapes, manufacturers' catalogues of standard building components, pricing information relative to material and labor, etc. The specific knowledge contained in this component will depend upon the type of application being developed, and even for a given application, the knowledge may be dynamic because of other considerations. As an example of the former, one need not represent properties of steel sections in an application meant to design concrete bridges. As an example of dynamism, some attributes of the products—cost being a prime example—may vary from region to region.

Also, some of the knowledge may be vendor dependent. In the case of cold-formed steel decks, for one, the properties may vary from vendor to vendor. In other cases the knowledge will be independent of the vendor. For instance, the cross-sectional area of a #3 rebar will be the same irrespective of the vendor. Structurally, there is nothing inherently fundamental about most of product knowledge. For instance, at least in principle, one can use a rebar having a diameter of 3.5/8". However, since the final design must be constructible, the current construction practices have to be reflected in the design process, thus necessitating this component.

1.6 Concepts

While developing a strategy or defining evaluation criteria, one may need to use some auxiliary concepts useful for encoding the problem-solving knowledge. To illustrate, architects and structural engineers often work in terms of geometric patterns during the conceptual design stage of buildings. The layout of a structural system may be strongly influenced by the presence of such patterns. Thus *pattern* becomes a concept which has to be recognized and accounted for while solving the problem. Another related example is the idea of *column lines.* Computer systems for generating floor framing schemes have employed this idea in the past to arrange columns in a regular fashion in the plan of a building. Such concepts should be explicitly identified in the knowledge-base of the system.

As noted earlier, $Cost/Value$ ratio can be used as an evaluation criterion to compare alternative solutions. $Cost$, $Value$, and the $Cost/Value$ ratio are all supporting concepts useful for formalizing the evaluation process.

1.7 Strategy

Strategy refers to the approach of solving a problem—the knowledge about how to use other knowledge. In essence, strategy is a structured form of anticipatory knowledge about the relationships among form, function, and behavior, that allows manipulation of the problem constraints to effect a desired outcome. The upshot of this component of the methodology is that one captures the experiential knowledge of the designers in a given problem domain. Coming up with the *form* of a design solution, which is a highly creative process that relies more on the ingenuity and experience of the designer than on the foundational knowledge in the domain, is accompolished largely through strategy.

A simple example will illustrate the usage of strategical knowledge. Recall that in Section 1.4 we deduced an expression for the minimum depth of a beam, d, from some behavior and performance considerations. Though mathematically it is equally valid to derive expressions for w or E instead, we implicitly recognized that expressions for w and E are not meaningful because, typically, d is the quantity that can be varied to satisfy the behavior and performance requirements. Hence, in order to block superfluous inferences from the represented knowledge, one also has to explicitly state how the represented knowledge can be used best.

Such control knowledge can be very important for the sake of efficiency; it may be used to pare down the search space of the feasible design solutions in the very early stages, based on some high-level considerations. Strategical knowledge, however, may be hard to acquire because it may be too implicit or obvious to the expert. The earlier example of w and E being relatively fixed quantities is a case in point.

Among the examples of knowledge in this category are knowledge about the decomposition of the problem, knowledge about when to formulate what constraints, and knowledge about how to utilize some concepts. As hinted earlier, an important aspect of strategy is anticipation; by anticipating the downstream decisions and the effects of present choices on them, one can minimize the revisions to the evolving design.

Heuristics are likely to be predominant in the knowledge contained in this component. Furthermore, problem-solving strategy may vary from designer to designer; hence any particular encoded strategy represents only a subset of candidate strategies. Since the information in *Structural Elements and Systems Knowledge* module is represented in a pure declarative—or task-independent—fashion, it should be possible to build different strategies that can operate on the same set of base-level statements. Thus, one can deduce design descriptions that use different approaches to arrive at the final solution, though all of them satisfy the applicable constraints. An instructive situation where this may be desirable occurs in the design of columns for multi-story steel buildings. One possible strategy for the selection of steel sections for usage at different floors is to choose those sections that result in the least amount of steel used (minimum weight strategy). Another possible strategy, arising from splicing considerations, is to choose from only those sections that have the same internal depth. (W14 sections, for instance, fulfill this criterion.) The computer system may present the options to the user and let him/her make the decision regarding which strategy to use, or, alternatively, may explore both the options and evaluate the resulting designs.

1.8 Reasoning with Constraints

Once the various types of knowledge described in the preceding sections are represented in a suitable format, one can reason from such knowledge to derive design solutions for a problem. The framework we propose for going about such a task is to formulate, propagate, and satisfy constraints. Constraints can be formulated based on information about the project context (e.g., location) as well as project-independent knowledge (e.g., general structural engineering principles). Thus, as demonstrated in Section 1.3, given the fact that the facility to be designed is a building (project-specific information), we can formulate the constraint that one must collect distributed vertical loads. Provision of a structural element `Floor Plate` will satisfy the constraint; however, through the process of propagation, one can formulate some additional constraints. For example, one now needs some structural element(s) that can collect the load from the floor plate and transfer it to the ground.

The constraints that can be formulated may arise from structural considerations or exogenous (e.g., architectural, mechanical, constructibility, etc.) considerations. Constraints arising in different domains may interact with each other, thus forming mutual constraints. As an example, consider the case of a floor system of a high-rise office building. In a typical floor system, mechanical and architectural elements (ductwork and ceiling, respectively) are also present in addition to the structural elements like girders and floor slab. Thus structural depth, mechanical depth, and ceiling height form a mutually constrained grouping such that, when taken in conjunction with the desired floor-to-ceiling height, they should not violate the restriction on the acceptable floor-to-floor height. The consequence of such a relation is that variation in the parameters of some domain may influence the decisions in other domain(s). Thus if the depth of the mechanical ducts is increased, one may need to reduce the depth of the girders or, alternatively, if the ducts were initially underneath the girders, they may now have to be passed through the girders.

The two top-level categories of constraints, namely *structural constraints* and *exogenous constraints*, can be further decomposed in accordance with the classification proposed by Luth [13]. The subcategories are diagrammatically illustrated in Fig. 1.1 and are described in the following two subsections.

1.8.1 Structural Constraints

Structural constraints include function, behavior, performance, geometry, product, and reliability constraints. Constraints arising from other subsystems (exogenous constraints) must be transformed into one of these types of constraints before their impact on the structure can be considered.

Corresponding to the primary function of the structure as mentioned in Section 1.1, *function constraints* refer to the loads and their locations relative to the ground. The loads can be described in terms of forces which have a magnitude, a direction, and a location in space. Some elements of

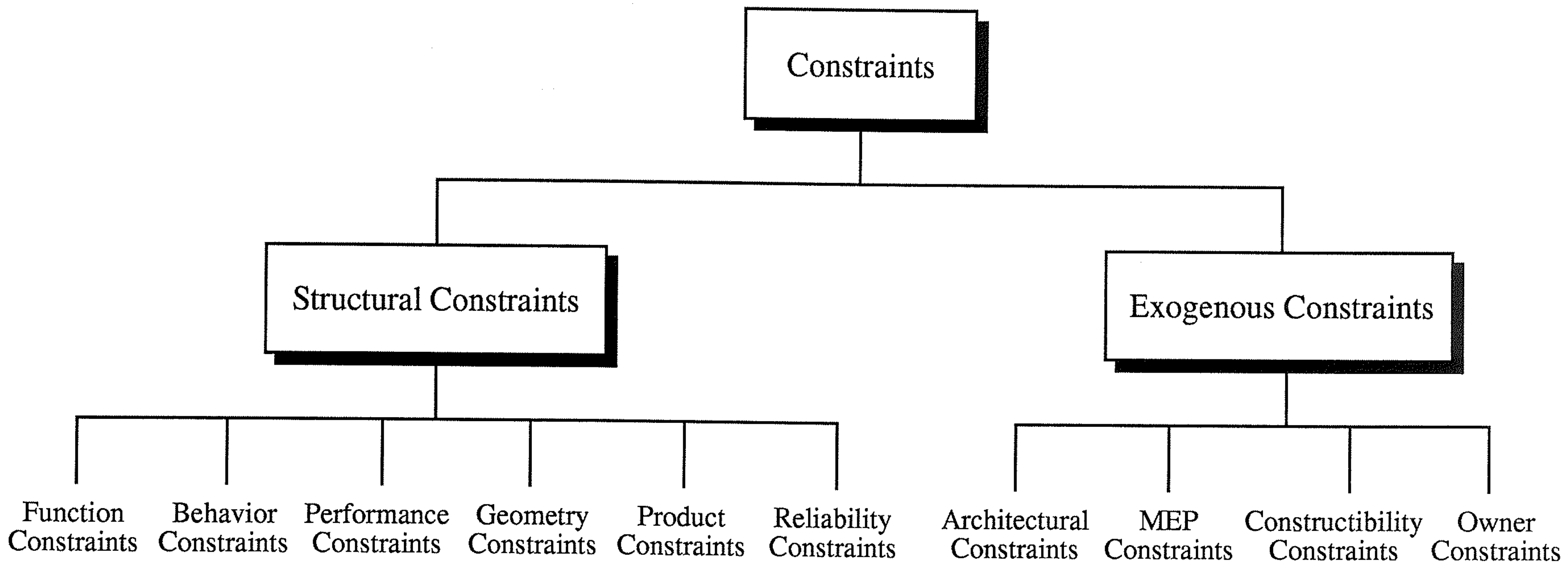


Figure 1.1 Constraint Classification. Constraints on the structural design may arise from both structural and exogenous considerations.

the structure may also perform an architectural function; for example, a slab, besides performing the structural function of carrying loads, may also be a functional object `Floor` from the architect's point of view. In such instances, there may be constraints on the physical object arising from its function in another domain.

Behavior constraints are derived from the behavioral part of the knowledge in *Behavior and Performance Knowledge* component. They are useful in determining the response of the structure while it is performing its function of carrying load. The behavior is dictated by such fundamental principles as Hooke's law and principle of superposition. Behavior constraints are absolutely "hard" constraints—they cannot be relaxed under any circumstances.

Performance constraints are based on the knowledge related to specifications and other performance criteria in the *Behavior and Performance Knowledge* component. They place limits on the values of the behavior the structure exhibits when subjected to loads, and thus enhance safety and serviceability of the facility. If performance constraints are violated, one may have to vary one or more of (a) the structure topology, (b) member material, and (c) geometric properties, to alter behavior in such a way that the applicable performance constraints are satisfied. Performance constraints can be further divided into *serviceability* and *safety* constraints. Serviceability constraints limit, amongst others, the deflection, vibrations, and cracking of a member or structure. Safety constraints, on the other hand, limit the internal stresses (in the case of working stress design) in the member, or specify a relation between the member force demand and the member capacity for that type of force (in the case of load and resistance factor design for steel, or strength design for concrete).

Geometry constraints define the location and spatial relationships of the structural elements. Product knowledge, in many cases, can also be transformed into geometry constraints. Constraints arising in other domains are often a source of geometry constraints on the structural system. Concrete beams that must be spaced at a specified interval to accommodate a particular arrangement of forms, spacing limits on steel beams which are a function of the cost of fabricating connections, and limits on member sizes based on crane capability or shipping requirements are all examples of geometry constraints which result from consideration of constructibility.

Product constraints exemplify the spectrum of choices available concerning specific materials and members. They are typically a result of transformation of the knowledge contained in *Product Knowledge* component. *Structural Elements and Systems Knowledge* may also be a source of product constraints; for example, reinforced concrete and steel may be the only usable materials for a framed tube. In addition, the user may also impose certain constraints; for example, though both steel and concrete tubes may be possible, the user may want only the option of steel tubes to be explored. Many constraints in this category may originate within the construction domain also. An example of a constructibility constraint that transforms into a product constraint in the structural design domain would be the concrete strengths that can be produced in the area where the facility is located.

Reliability constraints allow exercising of engineering knowledge and/or judgment to account for the probability that the behavior of an alternative will be acceptable. Redundancy, which is a property of the structure related to its function, is an example of a qualitative gage of the reliability of a structure. If there is only a single path for the loads to follow, the structure is "non-redundant." If there are multiple load paths so that when an element in one path fails, the load can still be successfully transferred through an alternate path, the structure is "redundant." Redundant structures are considered more reliable. Reliability of various structural systems is implicitly considered in the method of determining the seismic design loads. Some aspects of reliability are implicit in the load and resistance factors used in the limit state design of steel and concrete structures. For the most part, though, methods of explicitly incorporating issues of reliability during the design of structures have not been formalized.

1.8.2 Exogenous Constraints

Exogenous constraints are those constraints that are relevant to the design of the structure, but which originate in a domain outside structural engineering. The source of these constraints may be architectural, MEP (mechanical, electrical, and plumbing), owner, or constructibility considerations. Since buildings have many other important considerations besides the structural system, exogenous constraints have an especially pronounced impact in the case of buildings. Not all types of exogenous constraints described below may be present for all types of structures; for example, MEP constraints may not be applicable to bridge structures; however, they will be applicable in the case of power plants.

Architectural constraints arise because of the interconnection between architectural design and structural design of a facility. The architectural form often defines the geometric context for the structural system within the facility. The aesthetic expression may affect the geometric arrangement of the members within the structure for visual effect. Individual features of the architecture also result in significant constraints on the structure. For example, placement of columns may be ruled out in the central arena of an indoor stadium.

MEP constraints are very relevant in the case of high-rise buildings and many other types of structures. Each of the mechanical, electrical, and plumbing subsystems can be decomposed into major subsystems whose functions can be classified as origination, distribution (or collection), and delivery. The subsystems are a collection of components with physical attributes such as size and weight. Due to their size attributes, the MEP components compete with the structural and architectural system components for a share of the finite space defined by the building envelope (foundation, roof, and exterior walls). Thus one form of interaction is geometric. The weight attributes of the subsystem components become function constraints on the structure, thus presenting a second form of interaction. A third type of interaction occurs as a result of the behavioral characteristics of the subsystems within the context of the building usage. As an illustration, noise and vibration resulting from the operation of equipment may have to be isolated from adjacent spaces.

Owner constraints usually involve factors that affect the perceived value of the facility, the cost of managing the facility, or the schedule for the construction of the facility. Among these are constraints on vibration limits for floors, designation of certain areas as high load intensity areas, and the cost of modifying the structure to meet changing requirements. The owner may also have specific schedule requirements based on the need for the facility. In such a case an additional constraint on the conceptual design is that it should be constructible within the permissible amount of time.

Constructibility constraints result from the consideration of construction activities. Equipment capabilities, material availability, formwork considerations, etc., are all source of constructibility constraints. Moreover, because of the differences in the cost of labor, the available technology, and the available materials, as well as differences in the preferences of the designer and owner communities, certain structural systems are favored in some regions of the country. This preference is usually apparent in the prices that are associated with the systems and should be taken into account at the conceptual design stage. Many a times constructibility considerations are also implicit in the problem-solving strategy. For example, in the case of concrete, a new form is required for every difference in the shape and size of a structural component. In view of such a constructibility consideration, while generating solutions one may strive for uniformity in the shape and size of structural members.

1.9 Evaluation and Feedback

Since it is unusual for a design problem to have a unique solution, it is necessary to define some mechanism to determine the relative ranks of the generated alternatives and to critique them. In the past, the typical approach for assessing different solutions has been to define an evaluation function based on certain parameters (e.g., flexibility for future modifications, the speed of construction, the uniformity in the sizes of structural components, unit weight of the structure, etc.) that will be used to rank the solutions. Weights are associated with each of these parameters to reflect their relative importance. Actual values of these parameters are then computed for an alternative based on a system of reward and penalty as compared to some normalized values. The weighted mean of the actual values of the parameters for an alternative is then assigned to the evaluation function, whose value is taken as a measure of the intrinsic merit of an alternative.

We believe that the net result of such an exercise is only to provide an indirect measure of the *Cost/Value* ratio. The quantitative value of the evaluation function is not very useful for a human designer and the method of indirect measurement cannot be precise. For one, some degree of arbitrariness is introduced in deciding the weights and "normal" values of parameters. The problem is further complicated when qualitative responses of the user have to be accommodated. To illustrate, in response to a question about the availability of a certain material in a particular region, the user may have options of *Excellent*, *Good*, *Fair*, and *Poor*. The conversion of such values for usage in computing the evaluation function may not be universally acceptable.

One solution to such problems is to measure the effect of all relevant parameters in terms of either *Cost* or *Value*, and compute the *Cost/Value* ratio to get an indication of the merit of an alternative. To be precise in the *Cost/Value* analysis, one should use the costs and value based on the life-cycle of the facility. However, long term estimates of cost and value involve variables which are beyond the control of the participants in the design/construction process. Moreover, the *Value* part is often highly subjective and not amenable to measurements by a computer. For instance, the aesthetic value of alternatives may defy precise measurement. As another example, the *worth* of 'flexibility for future modification' in an alternative may vary from person to person. The compromise that we have adopted in the face of such difficulty is to associate an estimate of short-term cost with each alternative and present such data for all alternatives to the owner. The owner can then select one based on the respective perceived values of the alternatives. The default choice can be the one with the least cost.

Another aspect of evaluation is to critique the alternatives and provide feedback, if any, on how the alternatives can be improved. For instance, while determining the cost of erecting beams in a floor, the system may notice that all but two of the beams are of the same size and the other two are only slightly smaller. Upon further computation, the system may find that the extra cost of ordering/erecting the two smaller beams more than offsets the savings in the material cost. In such a case the evaluation process may result in a feedback to use the same beams throughout the floor. One may also try to anticipate downstream constraints while evaluating the alternatives and providing feedback. For instance, if the width of a concrete floor beam framing into a concrete column is less than the width of the column, there may be complications in erecting the formwork at the joint. The system can provide feedback about possible problems of this nature when evaluating an alternative.

1.10 Summary

To summarize, we regard the explicit definition and representation of function, form, and behavior of different structural systems and elements as essential for developing flexible conceptual design systems. Using these aspects one can model the structure, and when coupled with a model of the design process (i.e., strategy), one can efficiently generate solutions for diverse design problems. The reasoning can be carried out through the process of constraint formulation, propagation, and satisfaction. Knowledge of various types, e.g., quantitative behavioral description of structural elements and systems, design specifications, available products, etc., can serve as the source of constraints. Once the alternatives are generated, *Cost/Value* ratio can serve as the measuring yardstick for evaluating solutions.

The approach presented in this chapter can contribute towards developing general theories of the structural design process, as a specific instance of developing engineering design methodologies [16, 17]. In particular, the emphasis on explicit representation of the function, in addition to behavior and form, is very important. The flexibility of such an approach can be illustrated through a simple example. When designing a high-rise building, one can establish that there should be a structural system to resist the lateral loads. Resisting lateral loading can be further refined into resisting overturning moment and resisting shear. By choosing (a) axial force in columns in the line of applied loading as the mode of resisting overturning moment, and (b) flexure in columns as the mode of resisting shear, we can synthesize moment resisting frame as the structural system. Reasoning along the same line, we can include columns in the direction perpendicular to the applied loading as well for resisting overturning moment, thus "inventing" framed tube. Extending the example further, by changing the mode of resisting shear from flexure in columns to axial forces in inclined elements, we may even "invent" braced tube. Thus, through a process of deciding the basic behavior modes for satisfying functional constraints, we can compose structural systems to perform the desired function.

Chapter 2

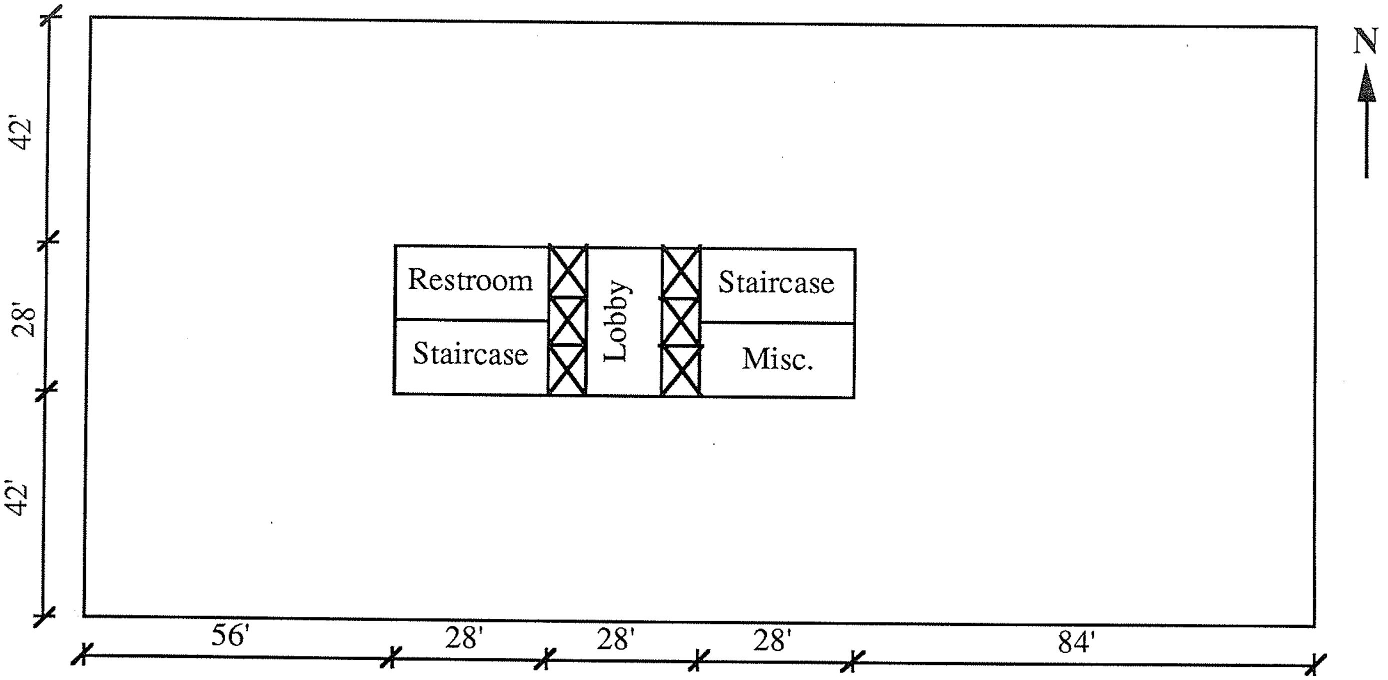
Application to Floor Framing Generation

In accordance with the primary function of any structure, the purpose of the structural system in a building is to transfer the loads from their points of origin to the ground. Depending on their direction, the loads are classified as either *lateral loads* or *gravity loads*. Schemes to transfer both types of loads need to be devised during the conceptual phase of structural design of a building. It is in the context of the transfer of gravity loads that the problem of floor framing generation arises.

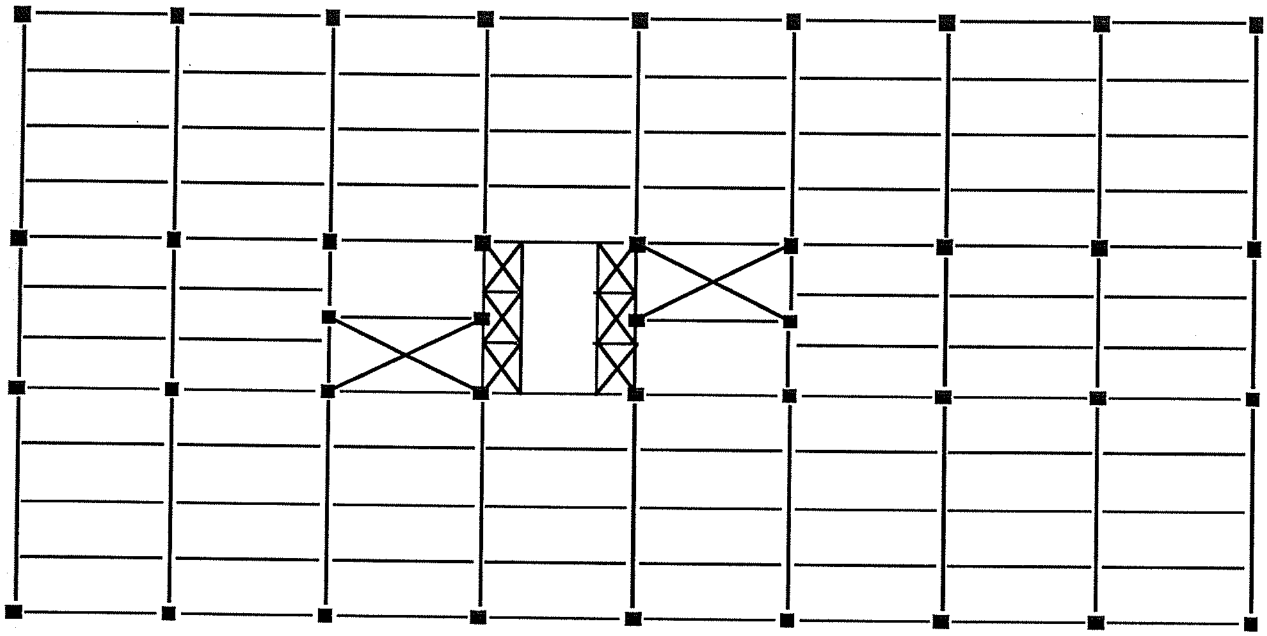
Floor framing generation involves providing a path to transfer the gravity loads to the ground through various structural elements in an architectural plan, while meeting the requirements imposed by other entities (such as the architect, the mechanical engineer, and the contractor) involved in the design/construct process. One of the tasks in the process is to determine the locations of columns, beams, and girders. Determining the locations of beams and girders, in turn, involves deciding on their respective orientations and spacings. The process can be illustrated with the aid of Fig. 2.1. Figure 2.1(a) shows part of a sample input (i.e., the architectural floor plan) to the process while Fig. 2.1(b) represents a corresponding partial output (i.e., the framing plan). (The thicker lines in Fig. 2.1(b) represent girders while thinner ones represent beams. Columns are represented by filled squares.)

Floor framing generation is used as a prototypical application in this chapter for illustrating the salient aspects of the methodology presented in Chapter 1. We describe the knowledge and the reasoning behind a computer system, FFG (for Floor Framing Generator), that generates floor framing schemes for steel office buildings that are rectangular in plan and have a single service core. FFG requires that all the architectural spaces (such as restrooms, hallways, staircases, etc.) within the plan be rectangular. Though the approach presented here has been developed in the specific context of high-rise steel office buildings that have rectangular plan shapes, it is extensible through appropriate modification of some concepts and constraints, and introduction of others to make it applicable to other types of buildings as well. In particular, with minor modifications one should be able to handle buildings whose plan is not rectangular, but can be divided into rectangular components. Handling arbitrary geometries, however, would require major enhancements.

The remainder of this chapter is organized as follows: We first present a brief review of relevant previous works in the next section. An elaboration of the various types of knowledge, constraints, concepts, strategy, and evaluation follows in the succeeding sections. Implementation issues are discussed in the penultimate section while conclusions from this work are drawn in the final section.



(a) Architectural Plan



(b) Floor Framing Plan

Figure 2.1: **Generation of Floor Framing Plans.** Structural elements like columns, beams, and girders are placed in an architectural plan to provide means for collecting and transferring gravity loads.

2.1 Background

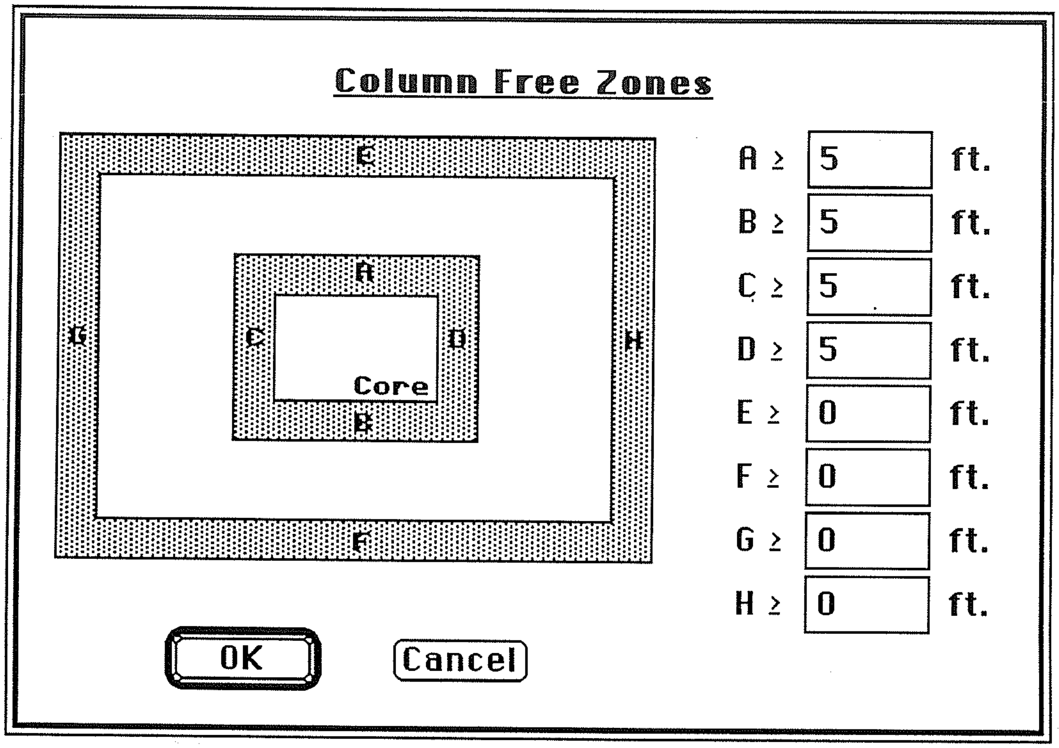
There have not been many knowledge-based systems in the past that have concentrated primarily on the issue of floor framing generation. Some of the well-known knowledge-based systems for preliminary structural design, such as HI-RISE [7] and DESTINY [8], do not perform floor framing generation; instead, the framing plans are supposed to have already been generated and provided as input to the system.

One system that did address the problem in detail was FLODER [18]. FLODER generates, analyzes, and evaluates floor framing plans for floor plans that can be subdivided into rectangular areas. For the generation part, FLODER works in terms of column lines whose placement is largely guided by the minimum and maximum economically feasible spans of the framing material. If the constraint on the maximum economic span of the material is violated, the situation is rectified by inserting additional column lines and thus subdividing the original span. The reverse takes place in case the constraint on the lower limit is violated. Girders are placed along the so generated column lines in both the orthogonal directions. If the spacing between consecutive girders exceeds the maximum economic span of the slab material, beams are generated parallel to the larger side of the rectangle. In case the floor plan is square, beams are generated in the X-direction. Again, the number of beams generated is such that the criterion of span limits are met.

FLODER represents a good start and emphasizes one important aspect of a good floor framing alternative: the necessity of meeting the economic span criterion. However, there are additional considerations that a human designer employs when generating solutions. Thus, FLODER's methodology needs to be enhanced to make it more useful for practical purposes. One disadvantage of FLODER is that in order to come up with an efficient framing system, it takes the liberty to rearrange the location of the mechanical shaft and hallways in the building plan. This is impractical as the location of the shaft and hallways is governed by many other (more important) considerations such as architectural constraints, maximum rentable space, building services, etc. The framing plan usually has to be worked around fixed locations of these spaces, and only in rare cases (e.g., where there is a significant saving in cost) are the locations altered.

A more recent work [19] attempts floor framing generation from the perspective of context-sensitive grammars. The *Structural Generators* in this work perform the spatial layout, using 30' as the preferred bay size, 23' and 35' as the minimum and maximum column spacings respectively, and a preference for symmetrical layouts. The knowledge contained in the generators, however, needs to be made more comprehensive and deep. "Hard-wiring" the values for span ranges also adversely affects the flexibility of the system.

Ideally, a general floor framing generator should be able to take constraints specified by the exogenous entities as input, and incorporate such constraints while generating potential solutions. For instance, as shown in Fig. 2.2, the architect may desire that there be no columns within 5' of the boundaries of the service core. Present systems do not provide flexibility to handle such exogenous constraints. As is described later in this chapter, FFG can handle some such considerations which arise outside the structural engineering domain. Also, the problem of "hard-wiring" is addressed in FFG by structuring the knowledge in terms of parameters that have certain default values which can be overridden by the user. With this background, we proceed to discuss the knowledge and reasoning used by FFG, which follows the concepts outlined in Chapter 1.



A ≥ 5 ft.
B ≥ 5 ft.
C ≥ 5 ft.
D ≥ 5 ft.
E ≥ 0 ft.
F ≥ 0 ft.
G ≥ 0 ft.
H ≥ 0 ft.

Figure 2.2: **Specifying Exogenous Constraints.** The architect may desire certain areas of the plan to be column-free.

2.2 Structural Elements and Systems Knowledge

In the case of buildings, satisfying the primary function of the structural system translates to generating schemes consisting of structural elements like floor plates, beams, and columns, to collect the incident and dead loads, and ultimately transfer them to the ground. FFG contains information about the attributes like *Function*, *Form*, and *Behavior* of generic structural elements and systems, based on which gravity load resisting schemes can be synthesized. The elements and systems for a scheme are so chosen that the desired function is performed effectively. As an example, FFG establishes the need for a structural element, `Column`, through reasoning based on function. From the fact that the structure is a building, it can be inferred that there will exist loads which act at a level above the ground. Thus, a transfer of load in the vertical direction is needed. Upon searching through the *Structural Elements and Systems Knowledge* module, FFG determines that three elements, namely `Hanger`, `Column`, and `Wall`, can perform the desired function. The element `Hanger` is described in Chapter 1. Description of the other two elements follows.

Column

Function	To transfer the applied loading in a vertical direction.
Primary Behavior	Axial Compression
Other Behaviors	Flexure, Shear
Form	1D Vertical

Possible Materials	Steel, Reinforced Concrete, Wood, Masonry
Supported By	Column, Wall, Transfer Girder, Foundation

Wall

Function	To transfer the applied loading in a vertical direction.
Primary Behavior	Compression
Other Behaviors	Flexure, Shear
Form	2D Vertical
Possible Materials	Reinforced Concrete, Masonry, Wood
Supported By	Wall, Column, Foundation

Since FFG is presently restricted to steel as the material for vertical support system, the choice of `Wall` is eliminated from consideration. This is done by an axiom which states that there should be at least one common member in the list of *Possible Materials* for an element and the list of actual material(s) being considered. That leaves `Column` and `Hanger` as the possible candidates. Since FFG does not currently have expertise for generating floor framing plans with hangers, these are also eliminated through another axiom which states that `Hanger` is unusable. Thus, it is clear that columns are needed. It should be noted, however, that one will have the option of generating solutions containing hangers also, if the system has the expertise to handle them. Reasoning based on function is general enough to handle such situations.

2.3 Product Knowledge

This component contains knowledge about the commercially available products that can be used for construction. Properties of steel floor decks and hot-rolled steel sections, along with their respective cost components, are examples of knowledge belonging to this category that is contained in FFG. Of the available options for the type of floor systems for steel buildings, we have restricted ourselves to composite metal decks, with either lightweight or normalweight concrete on top of a formed steel deck. In such an arrangement the deck acts as the form as well as positive reinforcement for the concrete. This arrangement is typical for floor systems in steel high-rise buildings [20,21] since it offers many benefits, including a more flexible system for wiring, availability of an instantaneous working platform, and protection of workers beneath because of the metal deck [22,23]. Composite action offers advantages such as reduction in the gage of the metal deck, structural efficiency, larger load capacity, capability for longer spans, and integral floor diaphragms [24].

As a specific example, for given combinations of (i) the depth of the steel deck, (ii) the gage of the deck, (iii) the depth of concrete, and (iv) the type of concrete, FFG knows about the following quantities:

- spanning capability of the deck,
- the self weight of the composite deck,
- the unit volume of concrete, and
- the recommended wire fabric.

In addition to the properties of composite metal decks, knowledge of attributes of wide-flange steel sections, like unit weight, cross-sectional area, radius of gyration, etc., is also included. Values of some other attributes, for instance the shear and moment resistance capacities, depend upon the grade of the steel and whether the action is composite or noncomposite. Accordingly, the *Product Knowledge* module contains the values of such attributes for different combinations of steel grade and type of action. (Note that the computation of resistance capacities of sections involves utilizing behavioral knowledge as well.)

2.4 Behavior and Performance Knowledge

Behavior and performance knowledge is indispensable in designing elements like beams, girders, columns, and the floor deck. For instance, when designing the floor beams (which are taken to be simply supported) carrying uniformly distributed load, the following behavioral relation is used to determine the end reaction, R:

$$R = \frac{wl}{2},$$

where w denotes the load intensity and l denotes the beam span. The end reaction, in turn, acts as a concentrated load on the girder on which the beam rests. The bending moment, M, at the center of the girder due to such a concentrated load is given by another behavioral relation:

$$M = \frac{Ra}{2},$$

where a is the distance from the point at which the load is acting to the nearest support. (Girders are also assumed to be simply supported.) If several beams are supported by the girder, the bending moment at the center due to all such concentrated loads is computed using another piece of behavior knowledge, namely the *principle of superposition.* In a similar fashion, the behavior knowledge is also applied to compute the deflection of the members resulting from the loading.

Performance knowledge specifies the limits on the observed behavior. We employ Load and Resistance Factor Design (LRFD) in FFG and a majority of the performance criteria are derived from the applicable design standards [25,26]. Examples of performance knowledge encoded in FFG are shown below.

- *Specifications pertaining to loads*: For instance, magnitudes of various types of loading (such as live load, partition load, etc.), load factors, and the load combinations for which the structure must be designed.

- *Specifications pertaining to safety*: For instance, resistance factors for various stress modes, effective flange width of a composite beam section, and strength reduction factors for shear studs.

- *Specifications pertaining to serviceability*: For instance, permissible live load deflection and the effect of shoring and cambering on serviceability requirements.

2.5 Constraints

The reasoning for generating the framing plans is carried out in terms of constraints described in this section. As elaborated in Chapter 1, the constraints are classified as either *structural* or *exogenous* depending upon whether they originate in the structural domain. Since a large component of the process of floor framing generation involves geometric decisions regarding placement of structural elements, many high level constraints originating from structural and exogenous considerations ultimately need to be transformed into their geometric implications. Therefore, in addition to detailing the constraints in the following sections, we also mention their influence on the geometry of the framing plan. Please note that the list of constraints described in this section is not comprehensive—the ones described here are the ones implemented in FFG. However, there are other constraints that are applicable to the problem but have not been implemented.

2.5.1 Structural Constraints

Several structural constraints result from the knowledge contained in the modules explained earlier. Loads are one obvious example of constraints in this category. In addition, there are several others as described below.

Minimum and Maximum Economic Spans: Various horizontal elements that can be used to bridge parts of a building have an associated economic span range, i.e., a range of spans for which a particular horizontal system is economically (as opposed to structurally) viable. The range may vary with such factors as the location of the building and the material. The minimum and maximum economic span criteria result from the behavior and performance constraints on structural elements and help to constrain the spacing of column lines.

Minimum and Maximum Economic Spacings: Similar to the economic span ranges, there are economical ranges for spacings in the case of beams. The range for beam spacing may be governed by the spanning capabilities of the overlying steel deck and the incident loading.

Minimum and Maximum Depths of Beams and Girders: Because of the need to pass mechanical ducts through the structural system, or considerations of overall building height, there may arise constraints on the minimum and maximum depths of beams and girders in the framing plan.

Fire Resistance: Corresponding to the design specification, there is a performance constraint regarding fire rating. This constraint can influence the thickness of the concrete on top of the metal deck, or can require spray fireproofing to obtain additional fire resistance.

Column Lines: A column line is a straight line defining potential locations for columns. Placement of columns is mostly constrained to be on the column lines. In essence, column lines are results of propagation of various other constraints.

2.5.2 Exogenous Constraints

Besides structural considerations, architectural, MEP (mechanical, electrical, and plumbing), constructibility, and owner considerations also influence the process of floor framing generation. Architectural considerations, in particular, have a pronounced impact since any improperly placed structural element may seriously interfere with the functionality of the building. In addition to those, this section contains MEP, constructibility, and owner constraints that have been implemented in FFG.

Architectural Constraints

Planning Module: Various elements in an architectural plan are typically aligned with a grid consisting of uniformly spaced lines in two orthogonal directions. The distance between two consecutive grid lines is not arbitrary; it is usually chosen to correspond with the standard dimensions for various building services such as lights and architectural fixtures. This distance is termed as the planning module and has typical values of 5' or 4'. The planning module may be influenced by the geographical location of the building (one particular value may be predominant in the region). For floor framing generation, the planning module defines an architectural constraint such that various structural elements should, as far as possible, coincide with the grid based on such a planning module.

Minimum Office Width: Based on the intended functional usage of the building, there is a limiting dimension that provides a lower bound on the minimum clear span in the functional areas of the building [27]. In the case of office buildings we denote such a quantity by the term *Minimum Office Width*. Minimum office width defines an architectural constraint on the floor framing which has to be satisfied by the column spacing in the framing plan.

Openings: Staircases, elevators, shafts, etc., are openings in the floor. Openings are important because no horizontal elements (such as beams and girders) can pass through them except at the edges. This constraint can result from mechanical considerations (vertically continuous shaft) or functional considerations (vertical transportation through staircases and elevators).

No Column Zones: For architectural or other functional reasons, certain areas in the floor plan may be designated as no column (or column free) zones—columns cannot be placed within the boundaries of such zones. For instance, all openings are no column zones. Similarly, lobbies are also no column zones.

MEP Constraints

Ductwork: This constraint has its origin in the MEP domain. The ductwork within the floor areas can either be restricted to pass through the structural system or below it. In the former case, the overall height of the building will be smaller due to the reduced floor thickness. This will result in smaller material costs as estimated by FFG. The latter, on the other hand, will be simpler to erect. FFG's capabilities with respect to estimating costs associated with punching holes (for the passage of ducts) in flexural members are minimal at present. Through manual computation, one can assess these costs and add them as penalty to the cost computed by FFG (in the case of ductwork passing through the structural system) to arrive at the total cost, thereby providing a basis for comparison of the two alternatives.

Constructibility Constraints

Constraints Pertaining to the Method of Construction: Incorporated in FFG are constraints that permit one to specify the construction of flexural members as either shored or unshored, cambered or uncambered, and noncomposite or composite. In the case of columns, one can provide the frequency of splicing in terms of number of stories. Also, FFG provides the option of choosing a design strategy such that sections of all columns have the same internal depth. This is useful for certain methods of column splicing in multi-story buildings.

Constraints Pertaining to Materials: In FFG, the grade of steel, the type (lightweight or normalweight) and strength of concrete, and the type of shear studs can be constrained based on the availability of materials to be used in the framing plans. The effects of these constraints will be reflected in the total cost and the unit steel weight of the structural system.

Many of the constructibility considerations are strongly influenced by localized construction practices and an explicit and comprehensive formulation of these constraints, which is globally applicable, is not possible. A few such constructibility considerations are incorporated in FFG through other constraints. *Column lines* are one such example, since the idea of uniformly spaced columns is beneficial from the constructibility viewpoint also.

Owner Constraints

Minimum Floor to Ceiling Height: The owner may set the minimum floor to ceiling height based on value considerations. In FFG, the height has implications for the loading and the length of columns.

2.6 Concepts

The concepts described herein are abstractions that perform supporting function in formulating the strategy or defining evaluation criterion. Additional concepts can be identified and the strategy can be modified accordingly to handle alternate geometries and different types of buildings.

Patterns: Schodek [27] states that there are often strong and easily identifiable patterns present in the functional organization of buildings and in the structural systems used. The patterns formed by the two are usually intimately related. Thus, while generating floor framing plans in an automated environment, there should be mechanisms for identifying common functional patterns and incorporating them in the structural schemes. Examples of common functional patterns found in office buildings include arrangements of office modules and arrangements of two parallel elevator banks in the core separated by a lobby.

Characteristic Dimension: A common structural pattern in buildings is composed of a series of uniformly spaced parallel lines defining locations of the vertical support system, thus forming an aggregation of repetitive bays. We denote the spacing between the parallel lines by the term Characteristic Dimension (CD). As stated earlier, functional and structural patterns are usually intimately related. Therefore, the CD's should ideally correspond to some architectural patterns in the building.

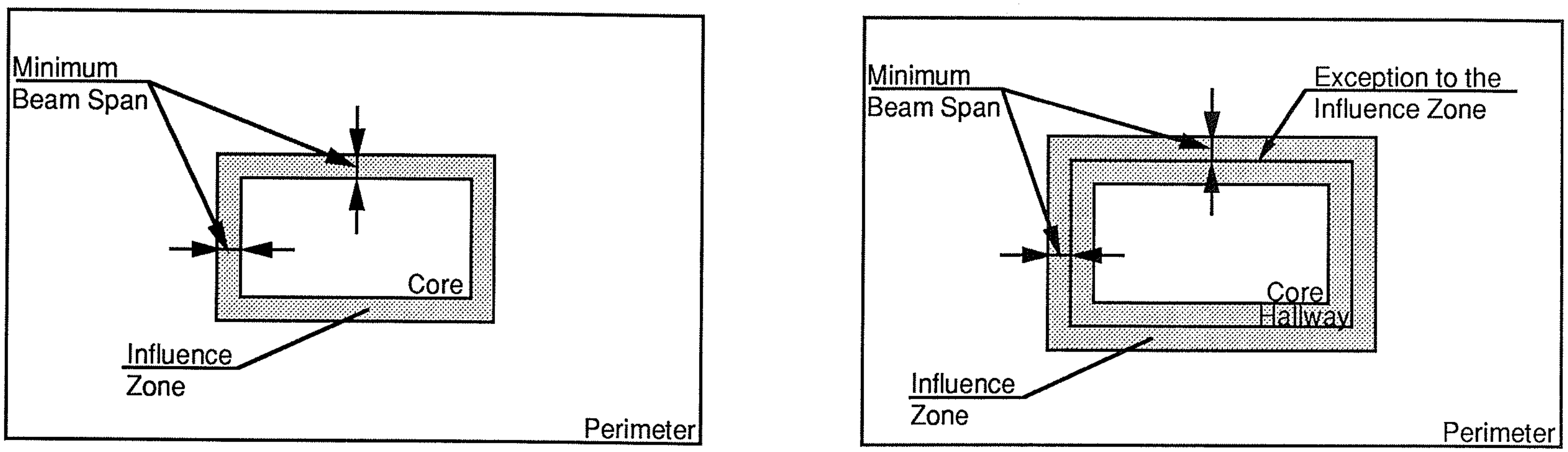
Influence Zone: The concept of influence zone is used to demarcate a certain region around the core in which columns cannot be placed. If no hallway is present around the core, influence zone is a rectangular strip with thickness equal to the minimum beam span. In case a hallway is present, the influence zone extends from the core boundaries to an imaginary boundary that is away from the hallway boundaries by a distance equal to the minimum beam span, with the hallway boundary itself being the exception. The two cases are illustrated in Fig. 2.3. The concept of influence zone arises from both functional and structural considerations. Placing columns within the influence zone will either result in interference with the movement around the core, or violation of the economic span limits, or both.

Core Partitions: Architectural spaces within the core are separated through partitions. Partitions provide better potential locations for placing columns as compared to the inside of architectural spaces, especially since the architectural spaces within the core are small and placing columns within them would seriously undermine their functionality.

2.7 Strategy

The problem of floor framing generation can be decomposed into the following tasks and subtasks:

- Generation of column locations
    - Generation of column locations through consideration of areas outside the core
    - Generation of column locations through consideration of areas inside the core
- Configuration of the floor system



(a) No Hallway Present

(b) Hallway Present

Figure 2.3 Influence Zones for Two Different Cases. Influence zones demarcate areas around the service core where placement of columns is not permitted.

  - Decision on the type of floor system
  - Generation of beam locations
  - Generation of girder locations
- Design of Members
  - Selection of steel grade and sizing of beams and girders
  - Selection of steel grade and sizing of columns

Elaboration of each of the tasks follows in subsequent sections.

2.7.1 Generation of Column Locations

The reasoning for generating column locations through consideration of areas outside the core is quite different from the one employed for generating locations through consideration of areas inside the core. Section 2.7.1 first gives a brief overview of the reasoning involved in generating column locations from outside considerations, followed by an elaboration of the individual phases. Section 2.7.1 describes generation of column locations from consideration of areas inside the core.

Column Locations Through Consideration of Areas Outside the Core

The following three phases comprise the generation of column locations through outside considerations:

1. Controlled Generation,
2. Testing, and
3. Modification.

The process of controlled generation entails pruning down an infinite search space of framing plans to a manageable size through some of the constraints and concepts discussed in Sections 2.5 and 2.6. This is accomplished by first generating sets of column lines in the North-South (NS) and East-West (EW) directions, based on the geometry of the plan. (The plan is taken to be aligned with the four directions.) Once the sets of column lines are generated, each set of NS column lines is considered in conjunction with each set of EW column lines to yield tentative column locations at the intersections of these lines. This results in multiple alternatives. The testing phase involves checking column locations in an alternative for constraint violations. If there are no violations, the alternative is acceptable. Otherwise, an attempt is made to modify the locations of offending columns in the modification phase. The modified alternative is retained if such an attempt is successful; otherwise, the alternative is discarded. Each of the remaining alternatives is considered for generation of column locations within the core boundary.

Two means are employed for generating column lines from outside considerations. One works in terms of patterns while the other depends on the decomposition of the plan into different zones. We first describe the former and follow it with the description of decomposition-based column line generation.

In pattern-based column line generation, column lines in a particular direction are placed at regular distances based on some characteristic dimension. The CD's may be extracted from architectural patterns or from other features within the plan. As an example of the former, backside of

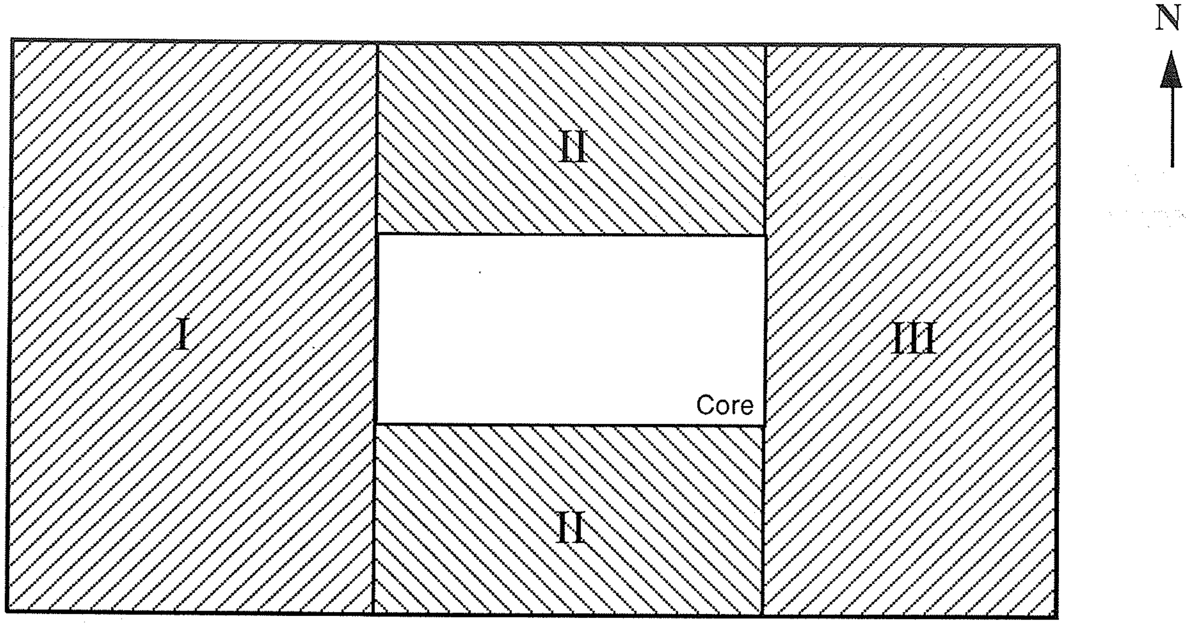


Figure 2.4: **Decomposition of Floor Plan for Generating Column Lines in the North-South Direction.** The decomposition defines three zones which are considered separately for column line generation.

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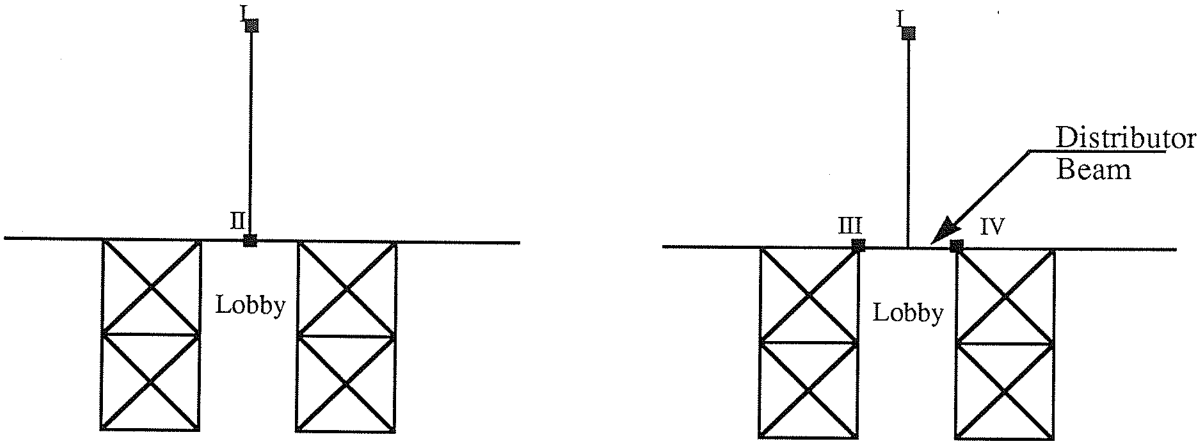
elevators are excellent locations for lateral bracing systems since there is no horizontal transportation across them. Thus the backsides provide us with good candidates for placement of columns, in anticipation of the lateral load resisting system (hereinafter referred to as lateral system). As mentioned earlier, a common architectural pattern involves two parallel banks of elevators separated by a lobby. The preference for uniformity, coupled with that for placing columns at the backs of the elevator banks, would thus imply that the structural grid uses a spacing equal to the one separating the backs of two parallel elevator banks. Thus, the distance between the backs of the elevator banks yields a candidate CD. Other potential candidates for the set of CD's include the width and the length of the core. The set of "raw" CD's extracted from these and other considerations is pruned to satisfy the constraints like minimum office space, planning module, and maximum economic girder span. Of the remaining set of CD's, a further subset is computed for each of the two directions (NS and EW) based on the criterion that the perimeter dimension should be an integral multiple of the member CD's.

Another mechanism for generating column lines is decomposition of the plan, facilitated by the assumptions of rectangular plan and core. When generating column lines in a particular direction, say NS, we can project the core boundaries in the NS direction to divide the areas outside the core into three separate zones as illustrated in Fig. 2.4. Each such rectangular subarea can now be reasoned about individually. One possibility is to use a uniform dimension that divides each of the three areas integrally, and also meets the constraints of minimum office space and minimum girder span. If no such dimension exists, then for each of the three areas we find respective largest dimensions that divide the areas integrally and still meet the constraints mentioned earlier. In the latter case the spacing of the structural grid will not be uniform throughout the plan.

Columns can tentatively be placed at the intersections of orthogonal column lines once sets of column lines are generated. However, some column placements may be found unsatisfactory.



(a) Column II is on the edge of a no colum zone.

(b) The intruding column is replaced by tw other columns and a distributor beam.

Figure 2.5: **Modification of Column Lines Based on Interference with Lobby.** An otherwise acceptable solution may be salvaged by modifying location(s) of unacceptable column(s).

For instance, if a column is placed such that beams (or girders) will not frame into the column in two orthogonal directions, the column will be laterally unsupported, unless the floor slab provides adequate lateral restraint. As another example, a column location may lie within the influence zone. The aim of the *testing* phase is to detect all such inconsistencies. All the potential solutions are checked to see if any of the constraints are being violated. If a solution contains one or more column locations within the no column zone, it is earmarked for modification phase; otherwise, the generated column locations are acceptable and define a feasible vertical support system outside the core.

If the testing phase discovers any column placements that violate some constraints, an attempt is made to modify the solution in the *modification* phase. For instance, if a column is placed at an edge of a lobby, then it may be possible to salvage the solution by replacing such a column with two columns at the two ends of the edge on which the column lines intersected. A distributor beam can be placed between the new columns which will also provide vertical support for linear horizontal elements in the direction perpendicular to the edge. This is diagrammatically illustrated in Fig. 2.5. Such modifications, however, may not always be possible. If the modification phase is successful, the modified solution is retained; otherwise, the generated solution is discarded.

Column Locations Through Consideration of Areas Inside the Core

For each of the solutions remaining after the testing and modification phases, appropriate column locations within the core can be determined. The operative concept when placing columns in the core is partitions. Partitions between different areas of the core yield ideal locations for columns—provided that the columns do not interfere with the functionality of some areas. Note that some columns at the core boundary or even inside the core may have already been placed prior to this stage as a result of intersection of column lines as described in the previous section. These have to be considered when deciding on additional column locations for the core.

Through reasoning about the geometry of the core, one can extract all the partitions in the core. Such partitions are potential column lines. The criterion of minimum beam span may be used to eliminate some parallel column lines that are too close to each other. The generation of column locations from the remaining column lines by intersection of orthogonal column lines is a straightforward operation.

2.7.2 Configuration of the Floor System

Upon generation of feasible alternatives for vertical support system, we can reason about the floor system for each such alternative individually. The biggest zone of the plan is considered first, since it has the potential of having the maximum impact on cost. A zone is defined as a contiguous part of the plan where conditions are the same everywhere and thus can be considered as a single entity for reasoning. Thus, orientations and spacings of beams and girders in a zone will be the same throughout. (Two alternative orientations of beams and girders are explored: (i) beams in the NS direction and girders in the EW direction, and (ii) beams in EW direction and girders in the NS direction.) For the biggest zone, a beam spacing within the range of minimum and maximum economic beam spacing is determined so that there are an integer number of full spans. A corresponding deck gage and depth can be selected for such spacing based on spanning capabilities of decks as contained in the load tables. The thickness and the depth of the deck will be the same throughout the plan for a particular solution.

The next step in the process is to choose the type of concrete, either lightweight or normalweight. Lightweight concrete, in general, has higher unit cost. However, since it needs less thickness of slab to meet fire resistance requirements, the required volume of lightweight concrete is less. Lightweight concrete can result in savings on other counts also, such as savings in material for other structural elements because of the reduced dead load, and savings in cladding costs because of reduced height of the building. For the lightweight concrete alternative the cost savings due to reduced concrete volume and reduced column steel are computed explicitly. Other savings (in flexural members, foundations, cladding, etc.) are estimated presently as 5% of the unit cost of lightweight concrete. Depending upon which alternative is less expensive at the end of this estimation process, lightweight or normalweight concrete is selected.

The orientation of the beams and girders is such that the girders align with the column lines (and thus rest on the columns) while the beams are in the perpendicular direction, supported at the end either by the girders or the columns. In any given zone, beams are spaced apart at a uniform distance consistent with the economic range of beam spacings. (Different zones within the same framing plan, however, may use different beam spacings.)

2.7.3 Design of Members

Two grades of steel are considered for beams and girders as well as columns: A36 and steel with a yield strength of 50 ksi (referred to as A50 in this report). The user may restrict the choice of steel grade to one of the two above, or may ask the system to explore both alternatives and select the least expensive one.

Selection of steel grade for beams and girders is based on the controlling criteria for sizing of beams and girders. If the sizing is governed by stiffness criteria, A36 steel is selected. If, on the other hand, strength criteria prevail, sizing is done for both A36 as well as A50 steels and the costs are compared before making a decision. For the chosen steel grade, the members are sized so as to meet both stiffness and strength requirements. Beams and girders may be designed as composite or noncomposite sections. In the case of composite design, FFG performs local optimization by opting for partially composite behavior (and providing fewer shear studs than needed for developing fully composite behavior) if the resultant section is sufficient to resist the flexural demand.

For selecting the steel grade for columns, columns at the top story of the building are sized for both A36 and A50 steel and the cost of the material is estimated. If A50 steel turns out to be cheaper, it is chosen for all columns without further cost comparison. If A36 columns are cheaper in the top story, an estimate of the total column steel weight (for all stories) is made for both A36 and A50 steel by designing the columns in the first story and assuming a linear variation in steel weight from the top story to the first story. The steel weights multiplied by the unit price of steel for the respective grades can then be compared to indicate the cheaper alternative. All columns are subsequently sized for the chosen grade every few stories, depending on the chosen frequency of splicing.

2.8 Evaluation

Once candidate solutions are generated, evaluation of the solutions is carried out to associate a measure of cost with them. The items comprising the total cost can broadly be categorized under the following heads.

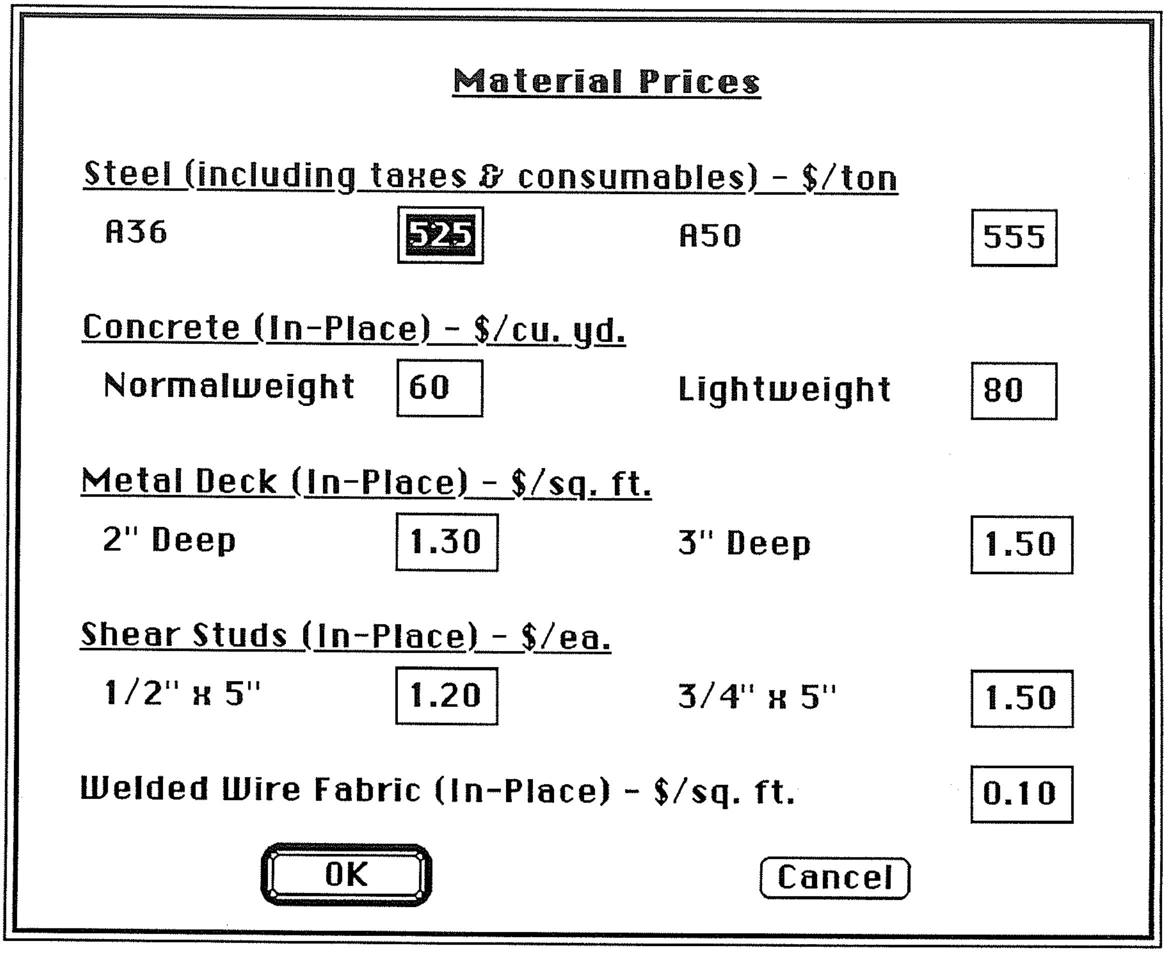
- *Material Costs*: These include costs of the metal deck, floor concrete, shear studs, welded wire fabric, and the structural steel for beams, girders, and columns. The cost associated with each of these items is computed by multiplying the unit price of the item in question with the corresponding units needed in the structure.

- *Fabrication Costs*: Fabrication cost of an element is based upon its type. For instance, the cost of fabricating a column of a moment frame differs from that of a column of a braced frame, which, in turn, differs from that of a gravity support column. Estimating fabrication costs is straightforward once the number of pieces of any given type and the corresponding fabrication price are known. (Fabrication prices are quoted in terms of pieces; thus if columns are spliced every 2 stories, a piece refers to a 2-story long column.)

- *Erection Costs*: Erection costs are based on the number of pieces to be erected and the project size. Depending upon the total steel weight of the building, the number of erectable pieces per day and the required crew size is determined. Given the data regarding price of erection per man-day, one can compute the total erection cost for the project.

- *Auxiliary Costs*: These are costs associated with shoring, cambering, fire proofing, and transportation. Some of these costs may be zero; for instance, the shoring cost will be zero if unshored construction is used. Shoring and fire proofing costs are based on the floor area. The cambering cost depends upon the number of pieces to be cambered while the transportation cost is based on the total steel weight.

The default unit price for each of the above items is provided but the user has the option to change any or all of the values. Fig. 2.6 illustrates a sample interaction for changing unit prices of materials. In addition to the cost evaluation of different alternatives, information regarding (i) steel weight per square foot of building, and (ii) steel construction cost per pound of steel is also provided.



Material Prices

Steel (including taxes & consumables) - $/ton
A36 525
A50 555

Concrete (In-Place) - $/cu. yd.
Normalweight 60
Lightweight 80

Metal Deck (In-Place) - $/sq. ft.
2" Deep 1.30
3" Deep 1.50

Shear Studs (In-Place) - $/ea.
1/2" x 5" 1.20
3/4" x 5" 1.50

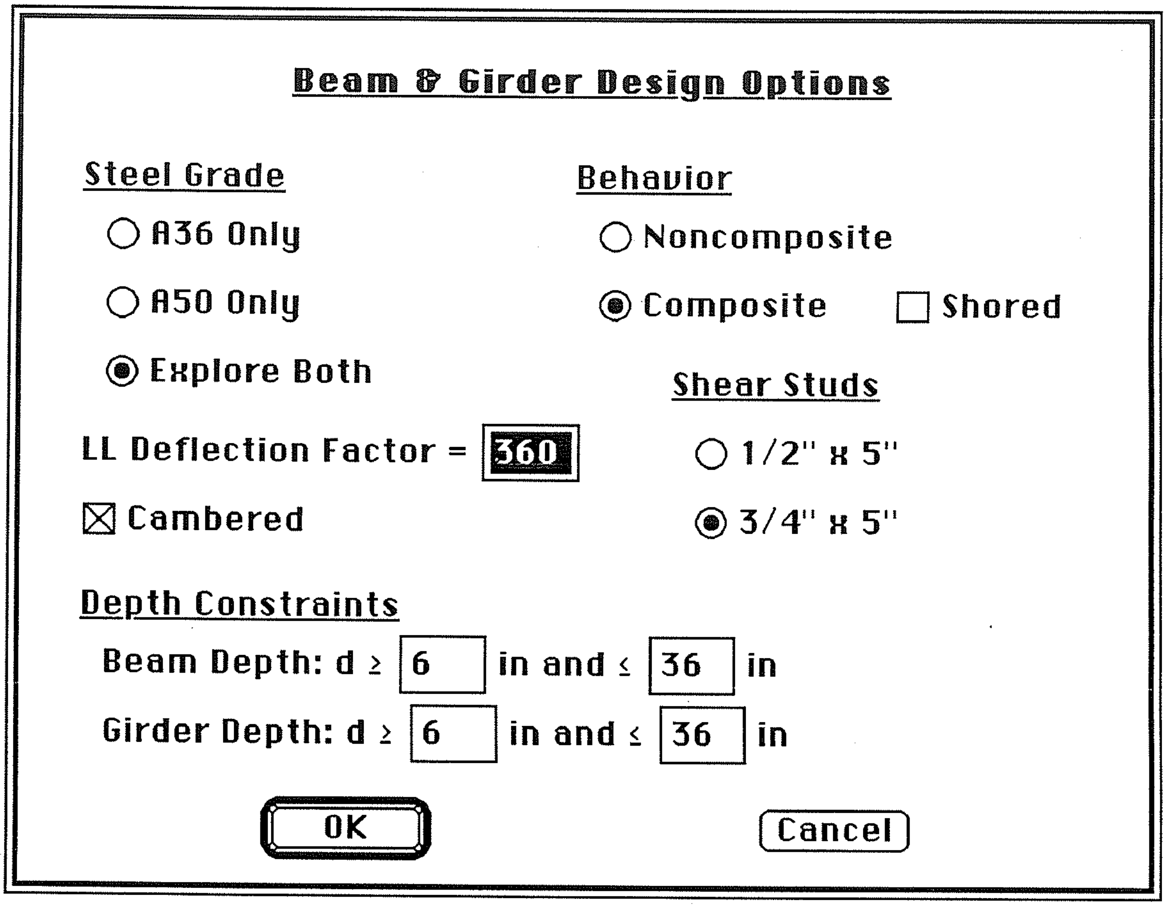
Welded Wire Fabric (In-Place) - $/sq. ft. 0.10

Figure 2.6: **Price Options.** Unit Prices of different materials can be set through the above dialog. Another dialog is available for setting other price options (e.g., fabrication, erection, fire proofing, transportation, etc.).

2.9 Implementation

The methodology described above has been implemented in a logic programming environment on a Macintosh II personal computer. The tool used for knowledge representation and automated reasoning in FFG is Epikit [28], a tool written in Common Lisp that employs KIF (Knowledge Interchange Format) language for representing knowledge. (KIF is similar to first-order predicate calculus.) For reasoning, Epikit provides several inference subroutines (based on demodulation, paramodulation, etc.) and several search strategies. The user interface of FFG has been developed using Allegro Common Lisp for the Macintosh.

The facts in FFG's knowledge base are structured in terms of various quantities like minimum office width, maximum girder span, etc., whose default values are provided. These default values can be overridden to allow complete flexibility. The philosophy behind the development of FFG has been to make it an "advisable" [14] system. Thus, the system can be forced to forego certain decision making processes and instead adopt the decisions made by the designer. Fig. 2.7 illustrates



Beam & Girder Design Options

Steel Grade

○ A36 Only

○ A50 Only

● Explore Both

LL Deflection Factor = 360

☒ Cambered

Behavior

○ Noncomposite

● Composite ☐ Shored

Shear Studs

○ 1/2" x 5"

● 3/4" x 5"

Depth Constraints

Beam Depth: d ≥ 6 in and ≤ 36 in

Girder Depth: d ≥ 6 in and ≤ 36 in

Figure 2.7: **Options for Beam and Girder Design.** Preferences for beam and girder design can be set through the above dialog. Other dialogs can be used to set design options for floors and columns.

one such example relevant to beam and girder design. An associated concept implemented in FFG is the idea of *modes* to accommodate users with varying degrees of expertise in the domain. The interaction with the system is different in different modes. For instance, in the *expert* mode the user has access to certain advanced options; e.g., quantities like crew size and erectable pieces per day can be altered by the user. In the *student* mode the explanation can be at a more elementary level and geared towards learning.

The interface of FFG is interactive and menu-driven. Fig. 2.8 shows the menus of FFG. The various menu items can be used to enter the input, set constraints, change the values of parameters, change default options, generate core configurations and framing plans, and view the output. The generation of core configurations is achieved through a library of standard core configurations meant for preliminary exploration.

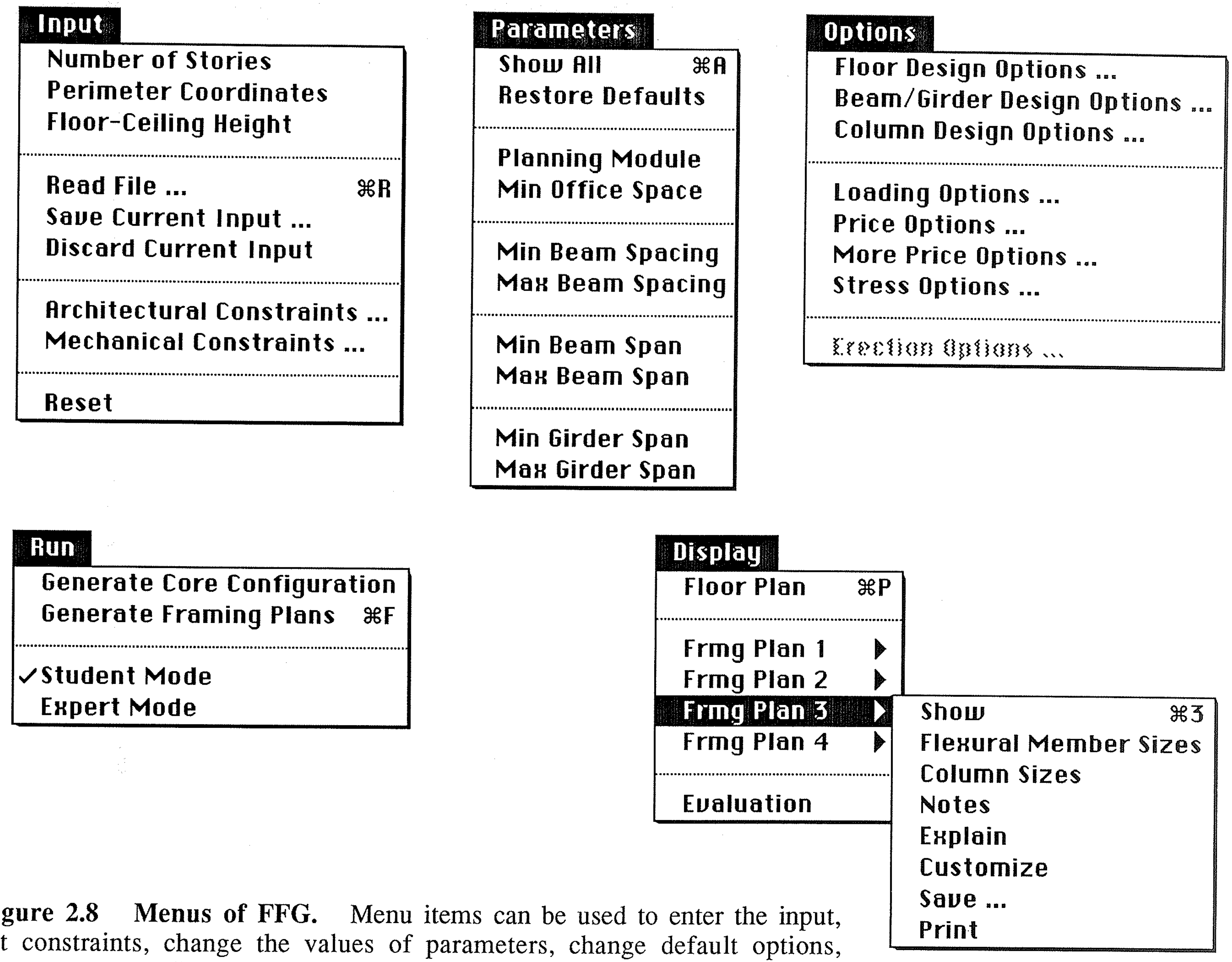


Figure 2.8 **Menus of FFG.** Menu items can be used to enter the input, set constraints, change the values of parameters, change default options, generate core configuration and framing plans, and view the output.

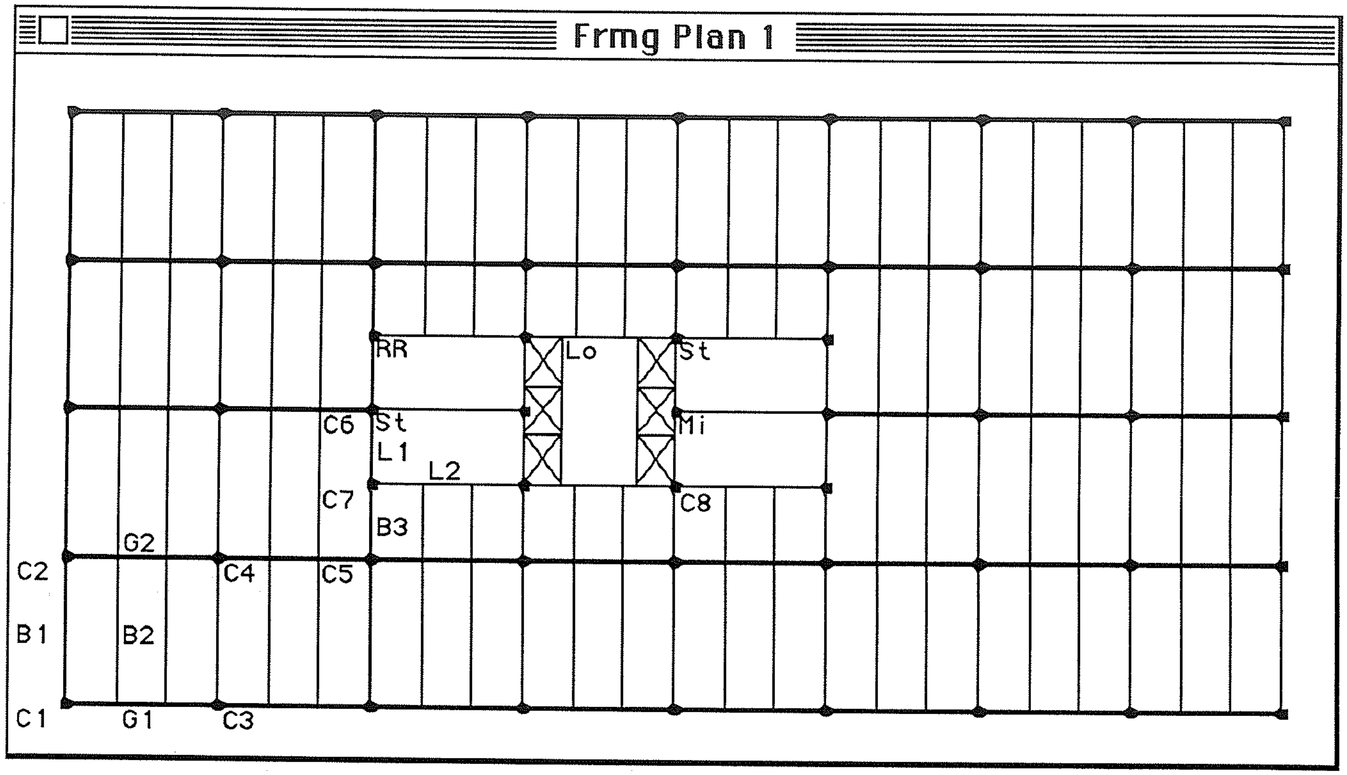


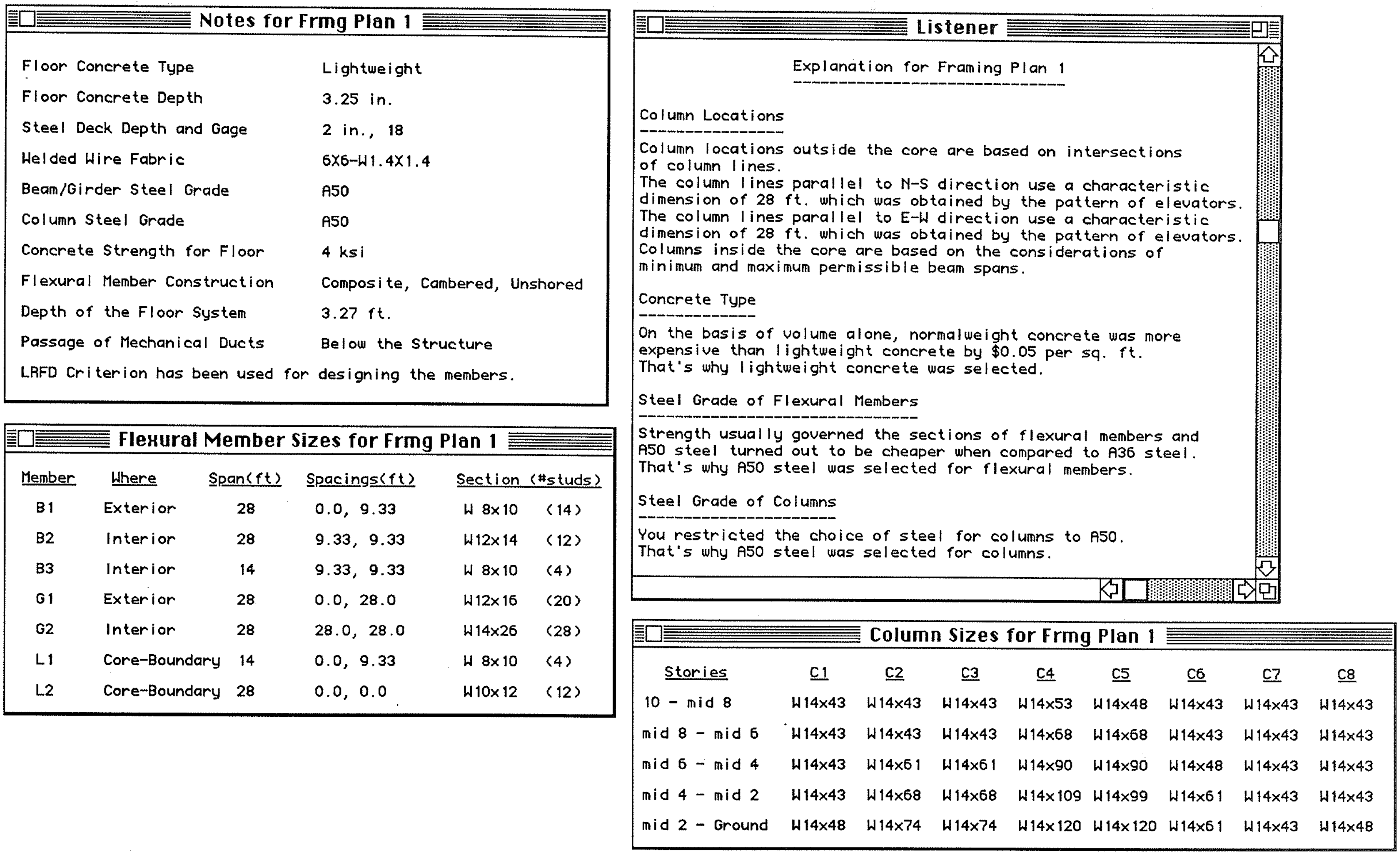
Figure 2.9: **Graphical Output of a Framing Plan Generated by FFG.** Sizes of columns and flexural members whose designations are marked above are shown in Fig. 2.10.

2.10 Example

The architectural plan shown in Fig. 2.1(a) is adapted from the plan of a real 10-story building and is used as a sample input to illustrate FFG's working. FFG generated four floor framing schemes for the plan, one of which is shown in Fig. 2.1(b). Another example framing plan is shown in Fig. 2.9 along with some auxiliary information in Fig. 2.10. A comparison of alternatives is presented in Fig. 2.11.

It is interesting to compare the solutions generated by FFG with the ones generated by the engineer responsible for the structural design. Of the four schemes generated by FFG, two matched with those generated by the engineer. However, there was one scheme that was generated by the engineer but not FFG; this scheme involved non-orthogonal girders. FFG is capable of generating solutions involving only orthogonal linear horizontal elements.

One of the ways in which FFG can be used is to estimate the effect of changing some design variant(s). For instance, we solved the above mentioned problem for two different cases to obtain a range of the unit steel weight for the resulting structural systems. First, to obtain the lightest system, the grade of steel for all members was restricted to A50, composite behavior was chosen for beams and girders, and concrete was selected to be lightweight. The resulting schemes had unit steel weight ranging from 4.24 to 5.08 psf and costs ranging from 6.74 to 7.38 $/sq. ft. For the other extreme, grade of steel for all members was restricted to be A36, noncomposite behavior was chosen for beams and girders, and concrete was selected to be normalweight, with everything else



Notes for Frmg Plan 1

Floor Concrete Type	Lightweight
Floor Concrete Depth	3.25 in.
Steel Deck Depth and Gage	2 in., 18
Welded Wire Fabric	6X6-W1.4X1.4
Beam/Girder Steel Grade	A50
Column Steel Grade	A50
Concrete Strength for Floor	4 ksi
Flexural Member Construction	Composite, Cambered, Unshored
Depth of the Floor System	3.27 ft.
Passage of Mechanical Ducts	Below the Structure

LRFD Criterion has been used for designing the members.

Flexural Member Sizes for Frmg Plan 1

Member	Where	Span(ft)	Spacings(ft)	Section (#studs)	
B1	Exterior	28	0.0, 9.33	W 8x10	(14)
B2	Interior	28	9.33, 9.33	W12x14	(12)
B3	Interior	14	9.33, 9.33	W 8x10	(4)
G1	Exterior	28	0.0, 28.0	W12x16	(20)
G2	Interior	28	28.0, 28.0	W14x26	(28)
L1	Core-Boundary	14	0.0, 9.33	W 8x10	(4)
L2	Core-Boundary	28	0.0, 0.0	W10x12	(12)

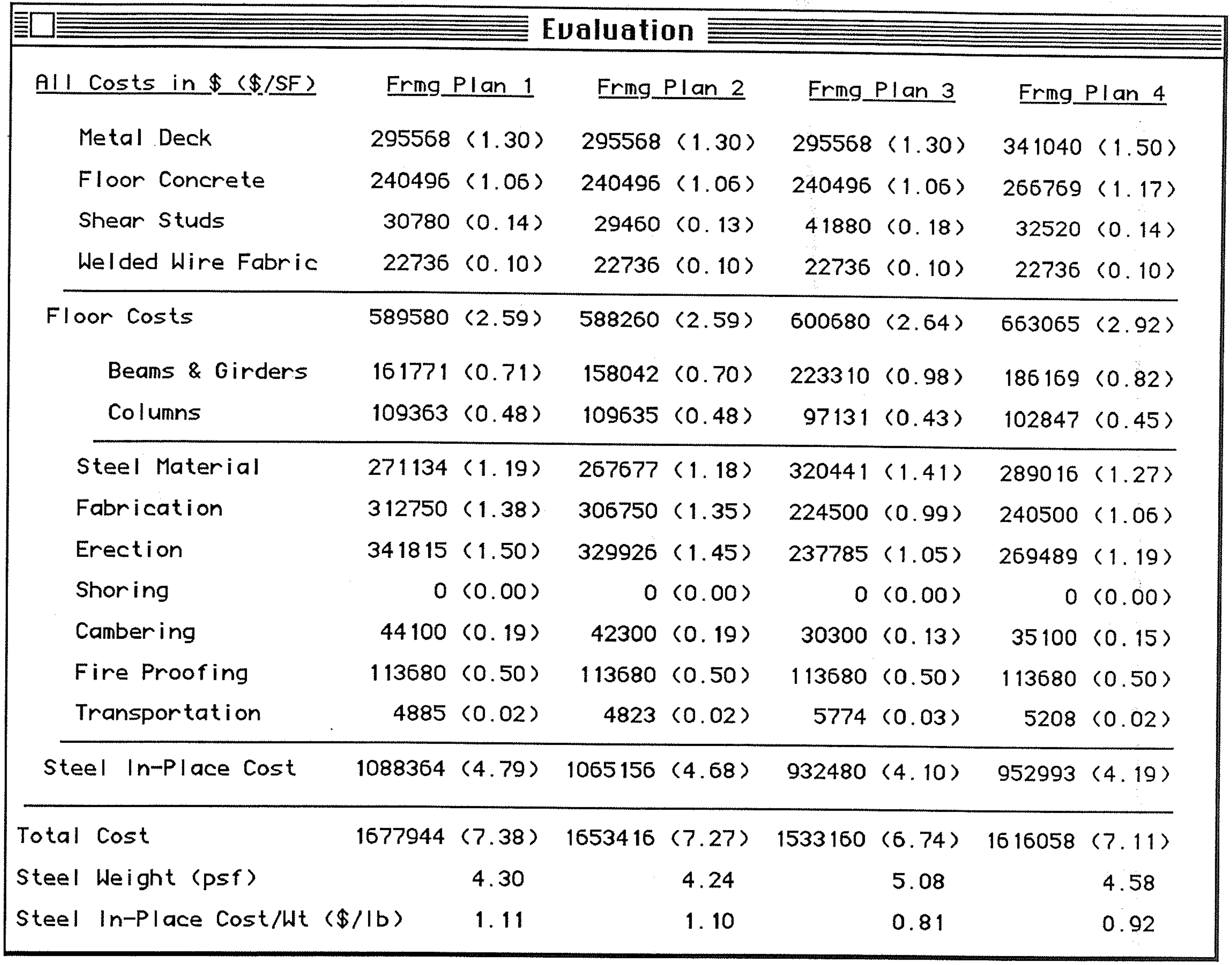
Listener

```
                    Explanation for Framing Plan 1
                    ------------------------------

Column Locations
----------------
Column locations outside the core are based on intersections
of column lines.
The column lines parallel to N-S direction use a characteristic
dimension of 28 ft. which was obtained by the pattern of elevators.
The column lines parallel to E-W direction use a characteristic
dimension of 28 ft. which was obtained by the pattern of elevators.
Columns inside the core are based on the considerations of
minimum and maximum permissible beam spans.

Concrete Type
-------------
On the basis of volume alone, normalweight concrete was more
expensive than lightweight concrete by $0.05 per sq. ft.
That's why lightweight concrete was selected.

Steel Grade of Flexural Members
-------------------------------
Strength usually governed the sections of flexural members and
A50 steel turned out to be cheaper when compared to A36 steel.
That's why A50 steel was selected for flexural members.

Steel Grade of Columns
----------------------
You restricted the choice of steel for columns to A50.
That's why A50 steel was selected for columns.
```

Column Sizes for Frmg Plan 1

Stories	C1	C2	C3	C4	C5	C6	C7	C8
10 - mid 8	W14x43	W14x43	W14x43	W14x53	W14x48	W14x43	W14x43	W14x43
mid 8 - mid 6	W14x43	W14x43	W14x43	W14x68	W14x68	W14x43	W14x43	W14x43
mid 6 - mid 4	W14x43	W14x61	W14x61	W14x90	W14x90	W14x48	W14x43	W14x43
mid 4 - mid 2	W14x43	W14x68	W14x68	W14x109	W14x99	W14x61	W14x43	W14x43
mid 2 - Ground	W14x48	W14x74	W14x74	W14x120	W14x120	W14x61	W14x43	W14x48

Figure 2.10 Auxiliary Information for Framing Plan 1. Non-graphical information accompanying a framing plan can be viewed through additional windows.



All Costs in $ ($/SF)	Frmg_Plan_1	Frmg_Plan_2	Frmg_Plan_3	Frmg_Plan_4
Metal Deck	295568 (1.30)	295568 (1.30)	295568 (1.30)	341040 (1.50)
Floor Concrete	240496 (1.06)	240496 (1.06)	240496 (1.06)	266769 (1.17)
Shear Studs	30780 (0.14)	29460 (0.13)	41880 (0.18)	32520 (0.14)
Welded Wire Fabric	22736 (0.10)	22736 (0.10)	22736 (0.10)	22736 (0.10)
Floor Costs	589580 (2.59)	588260 (2.59)	600680 (2.64)	663065 (2.92)
Beams & Girders	161771 (0.71)	158042 (0.70)	223310 (0.98)	186169 (0.82)
Columns	109363 (0.48)	109635 (0.48)	97131 (0.43)	102847 (0.45)
Steel Material	271134 (1.19)	267677 (1.18)	320441 (1.41)	289016 (1.27)
Fabrication	312750 (1.38)	306750 (1.35)	224500 (0.99)	240500 (1.06)
Erection	341815 (1.50)	329926 (1.45)	237785 (1.05)	269489 (1.19)
Shoring	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)
Cambering	44100 (0.19)	42300 (0.19)	30300 (0.13)	35100 (0.15)
Fire Proofing	113680 (0.50)	113680 (0.50)	113680 (0.50)	113680 (0.50)
Transportation	4885 (0.02)	4823 (0.02)	5774 (0.03)	5208 (0.02)
Steel In-Place Cost	1088364 (4.79)	1065156 (4.68)	932480 (4.10)	952993 (4.19)
Total Cost	1677944 (7.38)	1653416 (7.27)	1533160 (6.74)	1616058 (7.11)
Steel Weight (psf)	4.30	4.24	5.08	4.58
Steel In-Place Cost/Wt ($/lb)	1.11	1.10	0.81	0.92

Figure 2.11 Evaluation and Comparison of Alternatives. As the above example illustrates, a least weight solution need not be the least expensive one. (Structural members and the floor area inside the core are not included in the computations above.)

being the same. The resulting schemes this time had unit steel weight ranging from 7.05 to 8.39 psf and costs ranging from 7.62 to 8.19 $/sq. ft.

2.11 Summary and Closing Remarks

FFG illustrates that the methodology presented in Chapter 1 can be successfully applied to specific problems in the domain of conceptual structural design. Reasoning in terms of function, FFG establishes the need for structural elements based on the match between the requirements of the facility and the capabilities of structural elements. First principles behavior knowledge coupled with performance knowledge is used for the design of individual components, keeping in consideration what products are available for construction. FFG makes its decisions so as to satisfy many different types of constraints originating from diverse sources, including the structural and mechanical engineers, the architect, the contractor, and the owner.

One feature of FFG is that the need for recognizing architectural patterns is acknowledged. Functional organization of the elements of an architectural plan can form some patterns. Detection of such patterns and their incorporation in the structural system is a desirable goal and FFG works towards that goal. Also, FFG operates at a more comprehensive level of knowledge than some of its earlier counterparts. For example, it has knowledge about openings, planning module, and partitions, and can reason about location of vertical support systems in terms of such concepts. Thus, FFG recognizes that columns cannot be placed within an area like lobby and tries to modify locations of any tentative columns violating such criteria. Similarly, it avoids passing linear horizontal elements through shafts, staircases, and elevator banks, which are openings in the floor. However, in some respects, FFG is still incomplete. Allowing different load intensities in different areas of the floor plan, for instance, will enhance the utility of the program.

There are several additional concepts which human designers employ that are not incorporated in the approach discussed in this chapter. One such concept is symmetry. One can enhance the strategy to include a mechanism that gives preference to symmetric framing configurations. Another useful enhancement will involve generating solutions which include non-orthogonal linear horizontal elements as well. Additional concepts will have to be identified and incorporated for this purpose. It is important to note that all such enhancements can be carried out without modifying the pure declarative representation of fundamental domain knowledge contained in the *Structural Elements and Systems Knowledge*, *Product Knowledge*, *Behavior and Performance Knowledge* modules.

It needs to be reiterated that FFG solves a partial design problem in that it designs gravity load resisting systems alone and does not presently consider lateral load resisting systems. Work is in progress with regard to lateral systems. With the addition of lateral systems design capability, we anticipate to be able to compare the costs of gravity and lateral systems and estimate the "premium" associated with resisting the lateral loads.

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