SELECTION OF OPTIMAL COMBINATIONS OF PRECAST, PRESTRESSED CONCRETE COMPONENTS FOR SYSTEMS BUILDING CONSTRUCTION BY LINEAR PROGRAMMING

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To my wife, Nonyelum, for her encouragement and patience throughout the writing of this treatise, and to my late parents, Agha and Ugo, who gave me the right orientation in life.

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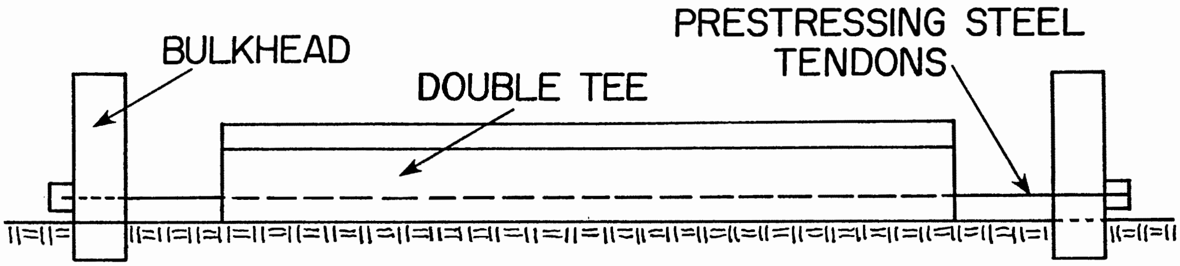
CHAPTER I

INTRODUCTION

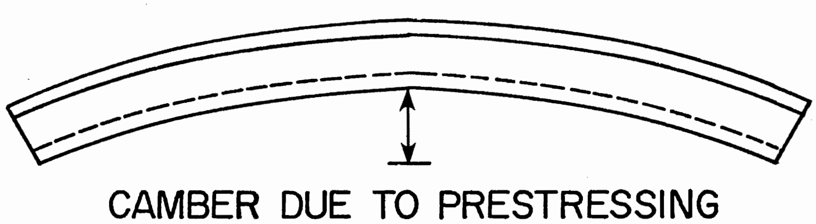
Prestressing, as applied to concrete structures, means the intentional creation of predetermined permanent stresses and internal moments in the concrete structure, so that internal stresses and moments resulting from service loads are confined within certain limits. Prestressed concrete is a concrete structure which has been subjected to prestressing before service loads act upon it. If the prestressed concrete structure is made at a place other than its final location in service, it is a precast, prestressed concrete structure.

In precast, prestressed concrete construction operations, steel cables (prestressing steel tendons) are stretched under large tension between two supports (bulk heads). Fresh concrete mix is then poured over these stretched prestressing steel tendons, and allowed to harden. In the process, the concrete is bonded to the steel tendons. When the steel tendons are cut they contract, thus subjecting the concrete to large compressive stresses. Figure 1(a) is a double tee which has been formed between two bulk heads. After the prestressing steel tendons are cut, Figure 1(b), the contraction of the tendons produces a bowing effect in the double tee. This effect induces compressive stresses in the bottom fibers of the concrete and tensile stresses in the top fibers.

There are many ways of anchoring the steel tendons to the bulk



(a) Double Tee Cast Between Two Bulk Heads



(b) Double Tee After Prestressing Steel Tendons Have Been Cut

Figure 1. Typical Prestressing Operation

heads. Figure 2(a) and (b) show two possible ways of doing this (1).[1] Figure 2(a) is a split cone wedge made from a tapered conical pin. Another grip made from a conical pin on which a flat surface has been machined and serrated, is shown in Figure 2(b).

Precast concrete construction often requires that concrete components be transported long distances. Therefore, it is economically desirable to make the components as light as possible. This can be achieved principally in two ways. First, by using high strength concrete to ensure small sections of components. Second, concrete aggregates (gravel, broken stones, pieces of non-reactive solid materials) weighing around 100 lb per cubic foot (light weight aggregates), should be used in precast concrete work. Many factors influence the strength of concrete mixes. The ratio of water to cement (water cement ratio), the type of aggregate used in the mix, and the temperature and moisture conditions (curing conditions) of the concrete structure especially during the first two weeks of the life of the precast concrete structure, all influence the strength of the concrete. The higher the density of the aggregate, the greater the weight per cubic yard of the hardened concrete. Because of the many factors which influence the properties of concrete mixes, there are many types of concrete.

Many different geometrical shapes, requiring different forms (steel forms, wooden forms, forms made of plastic materials) have been developed for precast, prestressed concrete construction. Double tees, flat slabs, el-beams, rectangular beams, concrete blocks to be used principally in the walls of buildings, core wall boxes and core wall panels for interior walls, stair landings and stair frames, are among such shapes. Some of these shapes are shown in Figure 3.

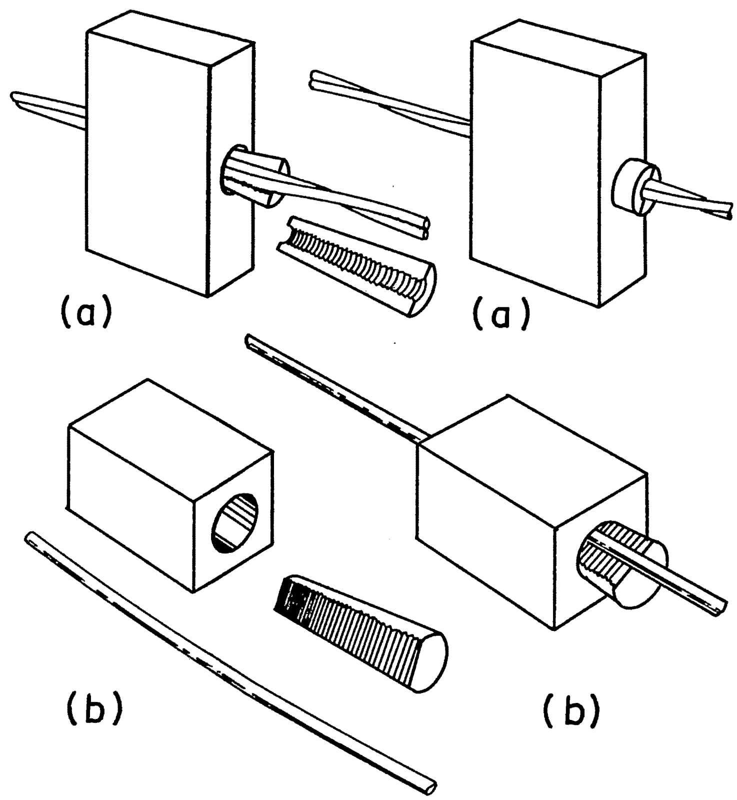


Figure 2. Gripping Devices for Prestressing Steel Tendons (1)

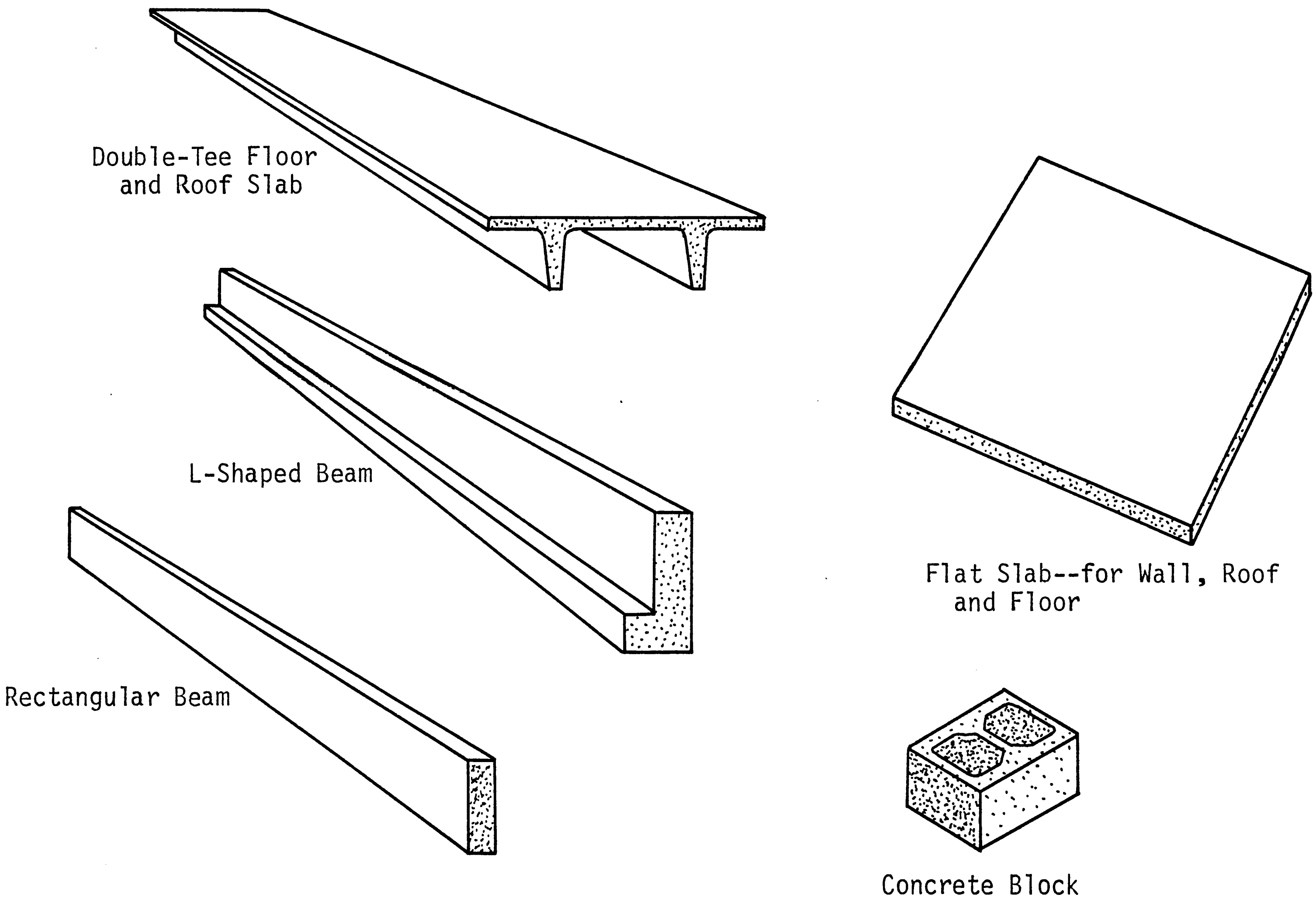


Figure 3. Precast Concrete Components

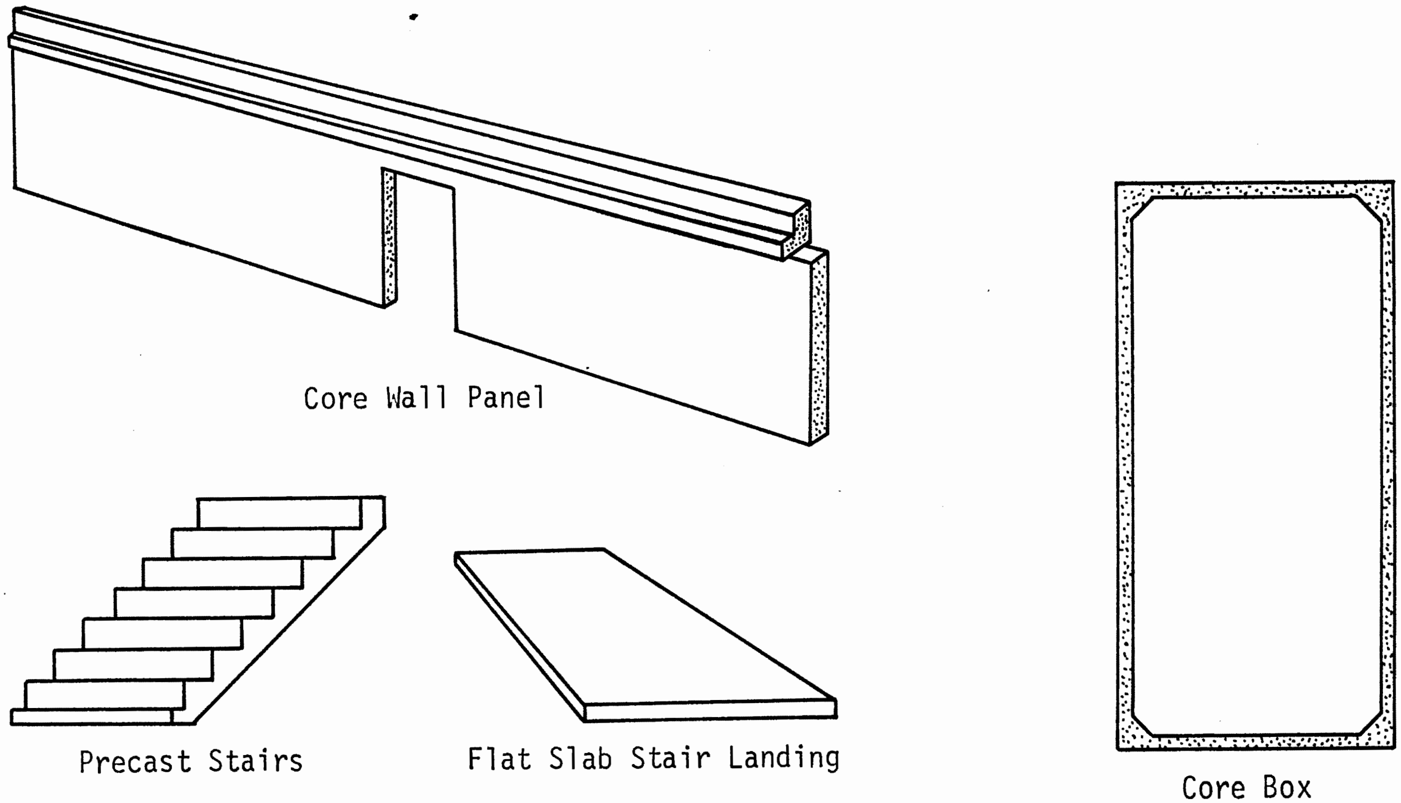


Figure 3. Continued

This treatise addresses the problem of selecting precast concrete components in such a way as to minimize the cost of a completed building.

During the planning stages of a precast concrete systems manufacturing enterprise, the selection of appropriate geometrical shapes and sizes of precast structural concrete members to manufacture is always a difficult decision. Once the choice of shapes and sizes are made and the proper forms purchased, it may take years before the replacement of the steel forms can be economically justified. In the late 1960's elaborate research projects were initiated by the United States Department of Housing and Urban Development (HUD) and the Illinois Institute of Technology Research Institute (IITRI) to determine structurally feasible geometrical shapes and modules which were economical and well fitted to the North American construction industry and labor practices.

If the research teams could have agreed on any one geometrical shape or module as the most economical, the uncertainties associated with the planning of concrete formwork for a precast concrete systems building (2) company would have been greatly minimized. However, the conclusions of the research teams regarding the economics of certain geometrical shapes or modules were contradictory.

Due to the experience in the precast concrete construction industry in both the United States and in Europe, one would anticipate the type of contradictions alluded to above. The research projects were executed under different organizations and management personnel. Also they were located in different areas of the United States. Location, environment, and the management of construction resources within the precast concrete plant can make a given geometrical shape or module more economical than another.

Thus, there exists a need for a method of analysis by the top management of a precast concrete systems building company, for the selection of economic combinations of geometric sections for new precasting plants. Such analysis should include a quantitative planning and decision model which establishes the relative economics of structurally feasible combinations of components or modules that make up precast concrete systems buildings. Additionally, such a model must contain specific provisions for the environmental constraints which are endemic to both the precast concrete plant and the marketing area in which the prospective precast concrete systems building company intends to operate.

Research at Oklahoma State University to develop such a quantitative planning and decision model by use of linear programming (LP)(3) has been completed. The LP model selects the economical and yet structurally feasible combinations of precast concrete components for precast concrete systems buildings. The model is a valuable aid to objective planning and selection of geometrical shapes (concrete forms) at a new plant location for a precast concrete systems building company. The model can also be used when steel forms replacement is to be considered.

The three phases of precast concrete systems building construction treated in this paper are plant operations, transportation of precast concrete components to the construction site, and the erection of the components at the building site. Structurally feasible combinations of precast concrete components which make up a building, formed the linear programming model. The effects which change in story height and the distance of a building from the precast concrete plant could have on the selection of economical combinations were also investigated. The precast concrete components that consistently formed the most economical combinations were recommended for precast concrete systems buildings development.

Chapter II presents a brief account of the development of concrete systems building construction. Chapter III is a review of literature on the applications of linear programming in Civil Engineering practice.

Chapter IV is on the formulation of the linear programming model developed in the investigation, while Chapter V addresses the problem of applying the model to the operations of an existing precast concrete systems building company, the Progressive Concrete Company (PCC). The real name of this company is disguised in this treatise.

The results of the various LP runs are presented in Chapter VI.

Chapter VII contains the summary and conclusions made from the research and recommendations for further research.

The references used in the dissertation are listed under "Bibliography".

The Appendix presents the data from the PCC, tables of quantities used in the models, as well as a brief description of a typical computer program. The description of the computer program is facilitated by the use of a listing of the typical program.

NOTES

[1]Numbers in parentheses refer to the Bibliography.

CHAPTER II

THE DEVELOPMENT OF PRECAST, PRESTRESSED CONCRETE CONSTRUCTION

Introduction

Initially precast concrete was used by engineers who were interested in building design and construction with limited knowledge of designing, forming, bracing, shoring and scaffolding, and placing concrete. Since precast concrete units could be inspected and tested for defective sections at the time of handling and erection, many engineers preferred to design structures in precast concrete. Other engineers reasoned that the problems and costs associated with forming, shoring, and placing cast-in-place concrete were excessive and that precast concrete construction was justified on the grounds of convenience in construction and cost.

Some Early Examples of Precast Concrete Construction

In 1900 (4, 5), a stable was built in Brooklyn, with precast concrete roof slabs 17 x 14 feet and two inches thick. The same precast slabs were used for partitions, cross walls, vents and manure pits.

In 1905 one of the early industrial applications of precast concrete in buildings was initiated in this country. During that year, a four-story building of complete precast reinforced concrete floor-and-roof system was constructed for the Textile Machine Works in Reading, Pa. By 1910 precast concrete was being used nation-wide in the construction of industrial buildings. The Unit Construction Co., St. Louis, Mo., constructed a large number of buildings completely built of precast units using a system called "Unit Structural Concrete Method," later named the "Unit System." The "Unit System" construction technique required that the connections between precast columns and girders be grouted to develop some continuity and rigidity. Conselman, the engineer and designer responsible for the development of the "Unit System," obtained more than 51 patents for the "Unit System," from 1910 to 1916. In 1911, a five story building was constructed for the National Lead Co., St. Louis, Mo., using the "Unit System." The five story building was completely precast, with design floor loadings of 500 lb per square foot. The interior and exterior columns, wall slabs, thin-shell channel-section floor slabs, and beams of this five story building were all made of precast concrete.

The Development of Precast, Prestressed Concrete Construction

The first prestressed concrete structures to be constructed in the United States were also precast structures. About 1886, P. H. Jackson, an engineer of San Francisco, California, obtained patents for tightening steel tie rods in artificial stones and precast concrete arch sections used as floors of buildings or side walls over excavations. In 1888, C.E.W. Doehring of Germany independently secured a patent for concrete reinforced with metal that had tensile stress applied to it before the slab was loaded (1).

In 1925, R. E. Dill of Alexandria, Nebraska, applied for a patent to produce precast, prestressed concrete members such as posts and slabs. Dill used a high tensile steel coated with a plastic substance to prevent bond (6). The steel was tensioned after the concrete had set, and was anchored to the concrete by means of nuts.

E. Freyssinet of France is credited with modern development of prestressed concrete. In 1928, Freyssinet used the first high-strength steel wires for prestressing. However, despite Freyssinet's ingenious development, it was still necessary to devise reliable and economical methods of tensioning and anchoring the steel wires before prestressed concrete construction could become popular.

From 1928 through 1940 adequate tensioning and anchoring techniques were invented. One of the engineers who made significant contributions in this area was E. Hoyer of Germany, by developing the Hoyer system. The Hoyer system consisted of stretching wires between two buttresses several hundred feet apart, constructing special forms to separate the units, placing the concrete, and cutting the wires after the concrete had hardened (1). In 1939, Freyssinet developed end anchorages and double acting jacks for tensioning wires. The Magnel system, developed in 1940 by Professor G. Magnel of Belgium, used two wires stretched one at a time and anchored with a simple metal wedge at each end.

Linear prestressing was initiated in the United States in 1949 with the construction of the Philadelphia Walnut Lane Bridge. Prior to 1949, circular prestressing of storage tanks was commonly used. Between 1935 and 1963, the Preload Company built about one thousand prestressed concrete tanks in the United States and other parts of the world (1).

By 1950, the use of prestressed concrete construction became common practice. Although there was only one precast, prestressed concrete plant in this country in 1950, there were 34 such plants in 1954. According to a survey by the Prestressed Concrete Institute (1), 229 plants were operating in this country by 1961. Some of these plants made both prestressed concrete components, and precast concrete blocks as well.

The Systems Building Approach to Precast, Prestressed Concrete Construction

The past ten years have shown an increased interest by governmental agencies and engineering institutions to improve the quality and economy of concrete construction by methods of mass production of precast, prestressed concrete buildings.

There was an acute shortage of residential houses in the United States in the 1960's. A report by Module Communities, Inc. (7) showed two-thirds of the population in the United States in 1968 was concentrated in the 228 metropolitan areas and that the total United States population would grow from 200 million in 1960 to 260 million by 1985. Thus, 20 million households would need residences by 1985. Consequently, President Johnson's message to the United States Congress in 1968 called for a new direction in the housing program. In his message to Congress, President Johnson emphasized the need to start and rehabilitate an average of 2.6 million private housing units per annum over the next 10 years. Records of the housing construction industry in the United States at that time showed the industry had not supplied over 1.5 million housing units per year during the preceding ten years. Thus, a new and faster approach to building construction was urgently needed.

The housing shortage in the United States in 1968 was similar to that of Europe after World War II. Post World War Europe experienced a severe housing shortage, especially for low-income groups.

The European countries' investigation of alternative methods of construction showed precast prestressed concrete systems buildings construction to reduce the cost of materials and labor. In addition, savings in time of construction due to mass production of structural elements was also determined. Thus, United States government agencies and institutions interested in industrialized concrete buildings had to carry out a thorough review of the European experience before developing or even approving most of the systems buildings in use in the United States today.

Development of Concrete Systems Buildings

Since 1946, the Federal Housing Administration (FHA) which is now part of the United States Department of Housing and Urban Development (HUD) has been involved in the evaluation and acceptance of manufactured and prefabricated housing. The FHA issued Structural Engineering Bulletins (SEB's) since there were no codes guiding this type of construction practice.

Three building systems developed in the North American continent since the 1960's have overcome the many constraints of residential construction. They provide aesthetically and functionally flexible buildings which are also economically feasible.

Habitat '67, developed in Canada is described by Fuller (8) as "... an exciting architectural utilization of prefabricated modules for residential construction; an escape from the typical staid cracker-box type of system."

Another system developed at approximately the same time was by H. B. Zachry Company of San Antonio, Texas. This was a box module system. A crash program was required involving the use of a checkerboard pattern of modules for the 21 story, 500 room Hilton Palacio del Rio. Construction had to be completed in nine months so the hotel could be ready for occupancy by April, 1968 for the opening of the Hemisfair. The first module was cast on August 15, 1967, while the final module was in place on December 20 of the same year.

The third system's building was developed by the Illinois Institute of Technology Research Institute (IITRI), through a demonstration grant awarded in 1967 by HUD (9). This study included an extensive survey of industrialized building methods used throughout the world. The system selected was a three dimensional open-top, concrete box module similar in concept to the H. B. Zachry System. A ten-story building with 78 apartments was modeled and several box unit models were tested.

Operation Breakthrough

On May 8, 1969, the United States Department of Housing and Urban Development announced a very comprehensive program to encourage industrialized housing concepts in the United States (8). The program, "Operation Breakthrough" (10, 11), was a total development program to resolve a multitude of problems associated with mass production of quality housing. It was to use modern design technology and contemporary approaches to financing, marketing, land use and management. The major objective of the program was to show that producers of housing in volume could realize economies of scale.

Operation breakthrough consisted of the three main phases listed below:

Phase I: Design phase which required that a precast concrete systems building met all the structural design criteria as specified by HUD.

Phase II: Construction of a structurally sound system. All the construction problems associated with the system were identified and resolved where possible.

Phase III: Private systems building companies were authorized by HUD to produce the systems buildings which had met the requirements of Phase I and Phase II.

Evaluation of European Systems

Realizing the great potential of the United States housing market, some European systems developers soon formed affiliations in this country. In January, 1968, the Cebus System was submitted to HUD, through the sponsorship of Laurel Concrete Products, Inc., Maryland. The Cebus System was designed by Tadjar and Cohen, based on a June 1966 French document "Joint Directives for the Acceptance of Building Systems with Large and Heavy Panels," by Cahiers du Centre Scientifique et Technique du Batiment. On May 29, 1968, HUD issued Structural Engineering Bulletin (SEB) No. 455 to accept the Cebus System.

Other European Systems which were studied by HUD are listed below (12, 13):

1. Balency (Thamesmead Project)
2. Bison (Concrete Limited)
3. Camus (Camus, Gt. Britain, Limited)
4. Coignet (Construction Edmond Coignet)
5. Laing (John Laing Construction Co.)
6. Tracoba (Industrialized Building Systems)
7. Wates (Wates Limited)

The Advantages of Precast, Prestressed Concrete Construction

The development of precast, prestressed concrete construction as a major segment of the construction industry since the 1950's has occurred due to its many advantages (14). One primary advantage is the reduction in formwork costs. Depending on geometrical configuration, size, material, labor, and the number of reuses, the cost of concrete forms vary from 33-1/3% to 60% of the total cost of each cubic yard of reinforced concrete in place. In most precast, prestressed concrete operations, forms can be used many times, thus drastically reducing formwork cost per use. Construction site labor costs can also be very much reduced by precast construction. Fuller (8) notes that construction labor could be reduced by 30 to 50% through the systems building approach. Other advantages of precast, prestressed concrete construction are listed below:

(1) The use of high tensile strength steel and high compressive strength concrete permits the use of smaller sections and less steel and concrete in prestressed components. Smaller sections also provide smaller dead loads (1).

(2) The use of high strength materials and the consequent reduction in dead load further extends the scope of use of

precast, prestressed concrete components by making longer spans possible and by substantially increasing the load carrying capacity of members.

(3) Precasting operations are usually conducted at ground level. This ensures close supervision of placing of concrete so that better quality control is provided.

(4) In many precast, prestressed concrete plants, precasting operations are accomplished in an enclosure. In such plants, the interruption of production due to bad weather is reduced.

(5) Reduction in labor costs is one of the major advantages of precast, prestressed concrete construction. Due to mechanization, less labor is required to build precast, prestressed concrete structures than cast-in-place reinforced concrete structures. Fuller (8) noted that in most European countries the construction site labor force can be reduced at least 50% and that box-type building systems in the U.S.S.R. showed a reduction as high as 80%.

(6) In the construction industry, reduction in time usually results in reduction of costs. A fast construction procedure provides at least three advantages:

   (i) Banks and other financial institutions show more interest for financial support for a construction project using such a procedure.

   (ii) Early completion of a facility to allow early use of if for rental property, a hotel or a restaurant could result in early recovery of a substantial part of the invested capital.

   (iii) Early completion of a project financed by borrowed money would normally reduce the interest costs. The literature on precast, prestressed concrete construction is replete with accounts of its savings in construction time (14, 15, 16, 17, 18, 19, 20, 21).

Some Historic and Current Problems Associated with Precast, Prestressed Concrete Construction

The availability of adequate lifting and transportation equipment was one of the problems associated with early precast concrete construction. Although the use of fewer heavier precast components reduces handling and erection labor, a precast component may not be heavier than the capacity of the largest available lifting and transportation equipment. Since heavy and economical equipments were not always available, the sizes of precast components were often limited.

Precast, prestressed concrete structures generally require extra design effort and a higher level of competency in structural design than ordinary reinforced concrete structures. Connections for precast, prestressed concrete structures require very careful design. In addition, every phase of the precast, prestressed concrete construction process must be programmed into a coordinated sequence of activities.

Lack of Uniformity among Design Codes

The absence of appropriate building codes and design standards has also retarded the progress of precast, prestressed concrete construction. Building codes differ from one political subdivision to another. For example, on the issue of live load requirements, D' Arcy (22) noted that in Oak Brook, Illinois, the code requirement for live load was 50 lbs per square foot which could be reduced for large supporting members down to 35 lbs per square foot. In the geographically close cities of Milwaukee and Chicago, a design for a superimposed live load of 75 lbs per square foot was required. Thus in a 90 mile radius, the specified design load in one area requires over twice the amount in another area for identical forms of loading. This lack of uniformity in live load design requirements forces the manufacturer of precast concrete components to assume the strictest code requirements within his marketing area. The assumption of the strictest code requirements tends to escalate the cost of precast concrete components and thereby reduce their popularity among contractors and builders.

Conflicting Highway Requirements on the Weight and Dimensions of Precast Members

The transportation of precast concrete components to erection sites is subject to many regulations regarding the use of the highway. Stringent transportation regulations tend to limit the sizes of precast concrete components and consequently the ability of a manufacturer to service an optimum marketing area. Various states have differing limitations on the widths of loads which can be allowed on the highway. A manufacturer of precast components in any one state may be confronted with different restrictions in adjoining states within his marketing area. Shipping widths as large as eight feet are generally permitted in all state and interstate highways. However, this eight feet upper limit can be extended up to 10 feet, 12 feet and even up to 14 feet in some states or among cities within the same state.

Most states allow lengths as large as 55 feet without special permit while others require that any length larger than 55 feet have special permit and escorts front and back and to limit travel to certain times of the day. Other states require only a simple permit for lengths larger than 70 feet.

Other limitations usually imposed on the transportation of precast concrete components are load limits and height limits. Although the general load limit is 20 tons to 22 tons, some states allow loads as large as 100 tons. A gross height (including height of truck and load) of 13 feet 6 inches can be transported without permit in some states while others place a maximum limit at 12 feet.

The lack of uniformity among codes makes the standardization of precast concrete components difficult. Standardization can increase the scope of application of precast concrete components and even enhance the expansion of the marketing area of a components manufacturer. Standardization can also reduce the cost of concrete forms. In an Engineering News Record (ENR) report (14), it was noted that if form manufacturers could follow a single pattern for any particular item for all customers, the cost of forms would decrease by 20%. Limiting the sizes of components increases the number of pieces required to construct a structure. Handling and erection labor, the number of joints and the quantity of materials needed to seal the joints, as well as the design effort, all increase with increase in the number of pieces. The result is an increase in the cost of a precast concrete structure, thus making it less competitive with other methods of construction.

Transportation cost is another problem associated with precast concrete building construction. Fuller (8) counsels that transportation distances be kept to a minimum, preferably to a maximum travel of one day round trips. Travel distances longer than one day round trips result in excessive transportation costs.

Some Economic Considerations in the Planning of a Concrete Systems Building Enterprise

One of the requirements for the success of a concrete systems building company is the existence of a large market to insure a large scale of production. Reliable market data which can distinguish between need and effective demand (23) must be accumulated before initiating a systems building enterprise. Reliable marketing information should state the number of building contracts that can be placed with the building industry. A systems building company should secure some contract agreement to insure adequate production volume for a reasonable time in the immediate future.

Concrete systems operations require high investments in manufacturing and transporting equipment. Unless a systems building company can be assured large production volume and continuity, high investments in equipment may not be economically justifiable.

Most concrete systems building companies in the United States use steel forms in their plant operations. These steel forms generally last from three and one-half to four years. Since the geometry of the forms affects both the aesthetic appeal and the manufacturing and handling problems associated with precast concrete components, it becomes an economic requirement for a concrete systems company to exercise sound judgement in the choice of forms.

Different geometrical shapes have different structural properties which affect the cost of the precast concrete components differently. Bryan (24) notes that in the United States, the double tee is being displaced by hollow core slabs for spans less than 30 feet. In selecting members for longer spans, Bryan states that for spans under 80 feet the deep double tee is preferred over the single tee.

The local construction requirements as well as the management of the construction resources within the precasting plant affect different geometrical shapes in different ways. This is why experts in the precast concrete construction industry have conflicting views on the economics of certain geometrical shapes or modules. For instance, Fuller (8), a structural engineer for HUD-FHA, states that box-module systems have the most difficulty in sustaining long-term success. On the contrary, the Illinois Institute of Technology Research Institute (IITRI) concluded from a HUD-sponsored research project (9) that box-like modular systems were the ultimate solution to the United States housing shortage problem. A survey conducted by the ENR showed that the double tee was the United States precast concrete "... industry's bread and butter product" (14). Dr. Gifford (25) of Concrete Limited, Great Gritain, who disagrees with the ENR survey (14) has this to say about double tees:

> A particular point which has always intrigued the author, and on which he would welcome comments, is the complete absence of double tees from Concrete Limited's products as sold--and the virtual absence of double tees as competition--various firms have, and some still do, make these units but they in no way are serious competition; we offer the unit but even on very large contracts it has never met the grade;

Since views differ on the economics of certain geometrical shapes, the selection of concrete forms for a new concrete systems building enterprise should be made only after a thorough evaluation of the local construction and structural problems affecting the economics of all geometrical shapes which are candidates for selection.

CHAPTER III

APPLICATIONS OF LINEAR PROGRAMMING TO CIVIL ENGINEERING PROBLEMS

Linear Programming (LP) is one of the most widely used mathematical decision tools in the optimization of scarce and valuable resources. Dantzig shows that before 1947 it was unknown although Fourier may have recognized its potential in 1823 (3). Its popular acceptance as a mathematical decision tool since 1947 is due to the following factors:

1. The development of electronic computers which reduce the computational burden required of manual solution of large sets of mathematical equations.
2. The development of the simplex algorithm by Dantzig.

Since the late 1950's, the interest of Civil Engineers in linear programming has grown very rapidly. This interest has been demonstrated by the publication of numerous research papers in which linear programming has been used to solve a wide range of optimization problems in Civil Engineering practice. Structural Engineering, Engineering Mechanics, Traffic Engineering, Hydraulics and Hydrology, and to a much less degree, Construction Management, are among the areas of Civil Engineering in which many realistic optimization problems have been solved using linear programming techniques.

This chapter reviews the literature relating to the applications of linear programming in the various areas of Civil Engineering. The inertia of the construction industry towards a popular adoption of quantitative management techniques is also discussed.

Romstad and Wang (26) and Moses (27) used linear programming to optimize the design of framed structures such as trusses, continuous beams and rigid frames. The objective of their linear programming model was to minimize the weight of the designed structure, subject to all allowable stress and displacement requirements. The computerized solution technique to the LP model is iterative. Thus, from a given solution, the solution variables are computed and used subsequently to modify the design parameters from a preceding acceptable solution to minimize the total weight of the structure. The iterations are terminated when no more significant reductions in the overall weight of the structure can be realized by additional iterations.

Reinschmidt and Norabhoompipat (28) and Farshi and Schmit (29) also studied the problem of optimizing the design of framed structures from the viewpoint of a global optimum. Farshi and Schmit demonstrated that the linear programming approach, when applied to a limited class of structures and failure modes, does offer an opportunity to obtain the global optimum design. Reinschmidt and Norabhoompipat proved that the linear programming optimization teahnique is a satisfactory method for seeking global optimums of structural design optimization problems.

Grierson and Gladwel (30) have presented a kinematic approach to the collapse load analysis of framed structures using linear programming. The object of the analysis was to determine the smallest load factor for which a collapse mechanism forms, subject to the following requirements:

1. The bending moments at every critical section of the structure are in equilibrium with the factored loads.
2. A sufficient number of plastic hinges have formed at the critical sections to transform the whole structure, or any part of it, into a collapse mechanism.
3. The fully plastic moment is not exceeded at any critical section of the structure. Consideration of all possible combinations of elementary mechanisms and hence, all possible collapse modes, was essential to the analysis.

Baldur (31) has demonstrated the application of an iterative method of optimizing a nonlinear multidimensional objective function subject to nonlinear inequality constraints to the design of structures. The method uses a sequence of linearized programs technique. The iterative procedure converges to the final point through a series of intermediate solutions in the feasible design hyperspace, which are least critical in regard to the linearized boundries. Every cycle of the iterative method solves a linear programming model problem. No transformations of the original problem specifications are required, thus allowing the engineer to exercise practical and intuitive judgement on the results during any stage of the solution process.

Cohn et al. (32) treated the analysis and design of plastic frames subjected to fixed, alternative and shake down loadings, as a linear programming problem. Both static and kinematic approaches were used in the analysis.

Abdel et al. (33) and Cohn and Rafay (34) have presented a linear programming formulation of second order collapse load analysis of elastic-plastic frames. In addition to the requirements of the analytic technique used by Grierson and Gladwel (30), the method used by Abdel (33) further includes the following:

1. The influence of axial forces on plastic moment capacities and on member flexibilities,
2. The secondary momemts created through the interaction of axial forces and deformations.

The solution method is iterative and starts from an upper-bound estimate to the failure load, with the solution to the problem being either equal to or a lower-bound estimate of the true failure load.

The Cohn and Rafay (34) model also uses linear and nonlinear programming techniques in conjunction with linearized and curvilinear yield conditions, respectively.

Kalinowski and Pilkey (35) have presented a deterministic, linear programming formulation of the problem of designing for incompletely prescribed dynamic loading. The Kalinowski formulation treats both steady-state vibrations and transient systems in which the structural equations of motion are linear. The computational procedure is iterative with the analysis at each iteration being a worst disturbance analysis.

Thakkar (36) formulated the design of non-cylinder composite prestressed concrete pressure pipes as a linear programming problem. The objective of the design was to minimize the cost of the pipes, subject to transient loading and possible service load combinations.

Many problems associated with the control of traffic in street network systems and inter-state highway designs have been investigated using LP models.

Killin (37) presented a general method by which linear programming may be applied to traffic estimation relating to interchange design. The LP model was based on a case study of the proposed interchange of the Federal Aid Interstate Route (F.A.I.) 03 with U.S. 50 near Seymour, Indiana. The desire to make a traffic movement was given a weight. The objective function expression was the linear sum of the products of these weights and the corresponding traffic volumes which make the movements. The objective function was maximized to yield the maximum traffic flow through the interchange. A lower bound was specified for the volume of traffic making any one of the possible movements.

Pinnel and Satterly (38) applied a linear programming model, the multi-copy missing model, developed by A. Charnes and W. W. Cooper, to the solution of the problem of arterial street analysis. The freeway volume was held at or below a fixed amount and thence developed the resulting optimum flow which was used to illustrate the LP formulation.

Wattleworth and Shuldiner (39) have demonstrated the application of linear programming to the assignment of traffic to routes in a network when the origins and destinations of the trips are known. An example of a network is presented on which no capacity restraint is placed on any of the links. An intersection model that permits time penalties to be assigned to individual turning maneuvers within the intersection was also presented. Charnes and Cooper (40, 41) have given a linear programming formulation of the traffic assignment problem in which capacity restraints on any set of links, in addition to the origin-destination requirements, may be satisfied.

Many papers involving the optimization of water supply systems by linear programming have also been published since the late 1960's. In 1969, Gupta (42) analysed a water pipe line system with a single source of supply. He formulated various combinations of pipe sizes and used a linear programming model to select the combination that minimizes the cost of pipe lines, subject to the requirements that customer demand for water usage and supply pressure be satisfied. Case and White (43) solved the same problem as Gupta but made specific provisions for the head losses in both the objective function expression and in the constraint inequalities.

Gupta, et al. (44) designed an optimum water distribution system using linear programming. This later formulation differs from the earlier work of Gupta (42) in that multiple supply points were used. Also the later paper uses an analogy of electrical network theory along with an algorithm developed in the paper. A water pipe line system with two supply sources were used to illustrate the LP formulation.

Yeh and Becker (45) applied linear programming to the parameter identification problem for unsteady open channel flow. They combined the linear programming with the influence coefficient technique.

Stephenson (46) has demonstrated a method of planning complex water resources projects using the principle of decomposition of linear programs. He used the Vaal and Tugela River Basins in South Africa as illustrative examples. A linear programming model was formulated for each river basin, and links between basins were incorporated in a master program. The objectives of the LP formulations were to optimize electric power plant capacity, reservoir capacities, and a water distribution pattern. The basin programs as well as the master program were solved successively numerous times before an optimum solution was obtained.

The Attitude of the Construction Industry to Mathematical Models

The indictment of the construction industry for lack of growth in productivity is well documented in the literature (47, 48, 49, 50, 51, 52). Invariably, a concomitant of this indictment is the enumeration of suspect factors which are claimed to be partly responsible for this lack of growth in productivity. For instance, the construction industry is traditionally unenthusiastic about the use of mathematical models even where such models have been known to yield substantial managerial and financial advantages (53).

In order to determine the attitude of the construction industry for the use of mathematical models, a survey of 23 construction firms was conducted by Adrian (47). The survey revealed a widespread lack of faith in mathematical models by members of the construction industry. Although 23 construction firms is not an accurate representation of the entire construction industry, the findings shown below indicate a slow acceptance of mathematical models.

The survey revealed that models such as tables for estimation of construction quantities were the most popular among the contractors covered in the survey. In fact, over 60% of the contractors used estimating models or tables of quantities. Network models which were used by over 43% of the contractors was second in popularity to estimating tables of quantities. The survey also revealed that network models were used more as project planning tools than as method models. Linear programming was used by only two of the 23 firms interviewed in the survey.

Some of the reasons given by the contractors for this lack of faith in mathematical models were the following (47):

1. Contractors' lack of knowledge of models and their applications.
2. Contractors' belief that models were inappropriate in their application to the construction industry.
3. Contractors' fear that the cost of implementing a model would exceed its benefits.
4. Contractors' fear that the models would conflict with union work rules and industry practices.

In 1965, Robinson (54) conducted a survey of 500 (mostly small) general contractors to evaluate their attitude towards the use of the critical path method (CPM). The survey showed that these companies were, in general, not using CPM and concluded that CPM use in the industry was concentrated almost exclusively among a relatively small number of large construction firms with annual volumes of construction over $10,000,000.

A decade after Robinson's survey, Davis (53) surveyed the top 400 U.S. construction firms to ascertain CPM use in those firms. The survey showed that not all those large companies were using network methods. The reasons given for the non-use of CPM were very similar to those already stated in Adrian's survey (47).

The author is persuaded that as contractors become more familiar with mathematical models and as the models become better adapted to the needs of the construction industry, the popularity of these models among construction contractors will grow. However, the diversity of the construction business and the great disparity in the levels of training of construction contractors will continue to be impediments to the popular adoption of mathematical models, at least for some time.

Linear Programming Applications in Construction Management

The remainder of this chapter presents brief summaries of linear programming applications in construction management.

A linear programming (LP) formulation of the project critical path network problem has been published by Charnes and Cooper (55), using network flow principles. Specifically, the formulation starts with a project precedence diagram, having activities on arrows. The project activities constitute the decision variables and the estimated mean activities' durations are the objective function coefficients of the decision variables.

Constraint equations are established by applying Kirchoff's law at every intermediate node. This implies that the algebraic sum of the flows in and out of every intermediate node is equal to zero. A unit positive flow is considered to be incident on the first node and a unit negative flow is assumed to flow out of the last node.

A maximum value of the objective function is then obtained to yield the project network critical path.

The Charnes, Cooper LP model has been applied to the time - cost trade-off problem of a project critical path network (56, 57, 58). However, much simpler techniques for computing the critical path and the necessary project network statistics have been well documented in the literature (59, 60, 61).

The bidding problem has been formulated as a linear programming problem by Stark (62). The objective of the formulation was to maximize the present worth of all expected future revenue accruing from payments on completed portions of a construction project, subject to the following three constraints:

1. The Bid Amount Constraint
2. The Unit Bid Constraints
3. The Rate Payment Constraints.

Upper and lower bounds were imposed on the values of the unit bid quantities. The Stark LP model has been published by Mayer et al. (63).

Ritter and Shaffer (64) treated the problem of blending natural earth deposits for granular embankment or base course in highway construction, as an LP problem. A solution to the LP model yields the quantities of each available natural earth deposit to be blended to produce the desired material at least cost to the constructor. An actual blending problem involving granular materials was used to demonstrate the use of the LP model.

A very interesting application of linear programming to the problem of planning a highway grading operation has been presented by Shaffer (65). The objective of the LP model was to determine which items of earth moving equipment in any selected contractor's equipment spread should be used on a grading operation. In addition, the LP model was to determine the combinations of equipment that should be used, when, where, and for what lengths of time the equipment should be used, in order to perform the grading operation on any project for the least total cost. Shaffer used a hypothetical, small-scale grading project to explain and demonstrate the necessary formulations. The hypothetical problem included:

a. The earthwork quantity

b. Equipment combinations

c. Available equipment times

d. Capital restrictions

e. Project completion time.

The extensive review of literature in this chapter shows that linear programming is a versatile optimization technique. However, it is not a cure-all for every optimization problem in Civil Engineering practice. To apply it to most practical problems, one needs to acquire a thorough understanding of the problem to be modelled as well as the techniques of LP formulation.

The next two chapters of this treatise discuss the problem of selecting precast concrete components for a precast concrete systems building company, by linear programming. Both the LP model formulation and its application to the operations of an existing precast concrete systems building company are demonstrated.

CHAPTER IV

MODEL FORMULATION

Introduction

A precast concrete systems building company, the Progressive Concrete Company (PCC), wants to select precast concrete forms to be installed at a new plant location. The company can afford to purchase only a limited number of steel forms.

The cost of a completed building is influenced very much by the geometry of the forms. Therefore, in order to remain competitive, the company needs to invest money only in those geometrical shapes which will ensure a minimum cost for a completed building.

The objective of the linear programming study is to select optimum combination(s) of steel forms which will enable the firm to satisfy the widest possible market for precast concrete systems buildings and precast concrete shapes, and which will ensure that the firm remains competitive. Since the PCC's systems buildings consist of seven major categories of precast components: floor, roof, wall, beam, center service core, stair and stair landing, there must be one form for each category. The PCC management planning problem is to select which forms in each category will produce the lowest cost building, taking into account highway load requirements, local building codes, and construction labor union contractual agreements.

In addition to taking full cognizance of all significant construction requirements at the area of the plant location, the solution to the linear programming model must accomplish the following:

1. Select the combination(s) of precast, prestressed concrete components which are the most economical for the PCC to manufacture at the chosen plant location.
2. Verify if the increase in the story height of a building affects the selection of the most economical combination(s).
3. Since the PCC may sometimes transport its precast concrete components hundreds of miles away from their precasting plant, to establish the influence, if any, which the distance of a building from the precasting plant has on the selection of the most economical combination(s).

For purposes of applying quantitative techniques to the solution of the PCC management problem, and also accomplishing the above three objectives, it was necessary to categorize the types of precast concrete systems buildings which were candidates for selection. The bases for categorization were height (number of stories) and distance from the precasting concrete plant. Five heights were considered: 1, 2, 3, 4, or 5 stories, and three distances: up to 75 miles, 75 miles to 150 miles, 150 up to 225 miles. Since there are five story heights and three distances, there are 15 categories of buildings for which solutions were obtained.

For each of the 15 categories of buildings, a linear programming model was formulated. Linear constraint functions were formulated to represent limitations on the following: Prestressing Steel Tendons (number of lineal feet); Reinforcing Steel Bars (number of pounds); Types of Concrete (cubic yards); Concrete Blocks (number of blocks in the building); Plant Labor (number of man hours in precasting the concrete); Erection Labor (number of man hours in erecting both the block walls and precast wall panels); Number of Truck Loads to transport the precast concrete components to the erection site. The decision variables of the LP models were derived from 48 different combinations of precast, prestressed concrete components, each combination including a type of precast concrete component from each of the seven major categories of precast components. Each LP model was solved as a cost minimization.

Results were obtained in two stages for each of the 15 building categories by formulating four different LP models for each category, or 60 LP solutions in all. For each of the 15 categories of buildings an LP was formulated in which three optimal combinations had to be selected. Subsequently, the selection of optimal combinations was limited to one selection. This was repeated two more times, thus providing a ranking (1^{st}, 2^{nd} and 3^{rd} choices) of the three most optimal combinations for each of the 15 categories of buildings.

Formulation of Decision Variables

To formulate the decision variables, all precast, prestressed concrete components that constitute the systems buildings are classified into the following groups:

Wall
Floor
Beam
Center Core
Roof
Stair Landing
Stair Frame.

Since each of these groups perform a definite function in the building, they will be designated as functional groups. Table I illustrates the relationship between functional groups and precast concrete components used by the PCC.

TABLE I

FUNCTIONAL GROUPS AND THEIR PRECAST CONCRETE COMPONENTS

Functional Group No.	Name	Precast Concrete Components
1	Wall	Double Tee Wall Panel, Flat Wall Panel, Blocks and Accessories
2	Floor	Double Tee Floor Slab, Flat Floor Slab
3	Beam	L-Beam, Rectangular Beam
4	Center Core	Core Wall Panel, Core Box
5	Roof	Double Tee Roof Slab, Flat Roof Slab
6	Stair Landing	Stair Landing
7	Stair Frame	Stair Frame

A functional group must contain at least two alternative precast concrete components before those components can be relevant to the model formulation. All precast concrete components which belong to the same functional group are said to be mutually exclusive alternatives. This means that in combining the components to make up a building, one and only one member of a functional group may belong to such a combination. Furthermore, a combination is deemed to be complete only if it incorporates one relevant precast concrete component from each functional group which has relevant components.

Table I shows that Stair Frame is the only member of the functional group named "Stair Frame". Since it is the only member of that functional group it is irrelevant to the analysis to follow. In contrast, Flat Floor Slabs and Double Tee Floor Slabs which all belong to the same functional group named "Floor" are mutually exclusive alternatives and are therefore relevant to the model development.

A building alternative is a combination of relevant precast concrete components formed with one component coming from each and every functional group possessing relevant components. In addition, a building alternative which is further identified by its story height and its distance in miles from the precasting plant of the PCC is named a decision variable.

There are five functional groups in Table I which have mutually exclusive precast concrete components. Since components can be chosen only one at a time from all five functional groups to form a combination, it follows that there are:

$$(NPC_1)(NPC_2)---(NPC_r)---(NPC_5)$$

combinations (building alternatives), where:

NPC_r = Number of Precast Concrete components in a functional group r.

r = 1, ---, 5.

Furthermore, there are:

$$(NPC_1)(NPC_2)(NPC_3)(NPC_4)(NPC_5)\cdot H\cdot L$$

decision variables, where

H = the total number of story heights studied in the investigation,

= 5.

L = the total number of building locations used in the model formulation,

= 3.

Implicit in the above formulation is the assumption that every building alternative and decision variable meet all the structural design and construction requirements at the given plant location.

A Mathematical Statement of the Linear Programming Model

A mathematical statement of the linear programming model follows presently:

Minimize: $\sum_{j=1}^{n} c_j x_j$

Subject to: $\sum_{j=1}^{n} a_{ij} X_j : b_i, \quad i = 1, \ldots, m$

$X_j \quad 0, \quad j = 1, \ldots, n.$

X_j is integer.

where:

C_j = the total plant cost plus transportation and erection costs of all precast concrete components used in the decision variable j.

X_j = a decision variable j.

n = the total number of decision variables.

a_{ij} = the amount of resource i required to make all precast components in a decision variable j.

b_j = the total available quantity b, of a resource type i.

m = the total number of resources used in the model formulation.

: means $\leq$, =, $\geq$.

The linear sum,

$$\sum_{j=1}^{n} C_j X_j,$$

is called the objective function or the merit function. It is a mathematical statement of the criterion on which the decision to select a decision variable is based. The decision to select any decision variable X_j is subject to the requirements that all the inequalities and equations: $\sum_{j=1}^{n} C_j X_j$, the constraint functions, be satisfied. Both the merit function and the constraint functions are linear. There are m linear constraint functions used in the model. In the sequel, the words equations and inequalities will be used interchangeably unless there is need for a more specific usage.

It is significant to note that in the mathematical statement of the model, all the decision variables are constrained to take on only integer values. A linear programming model in which all decision variables must take on only integer values is named an integer linear programming (ILP) model. If some, but not all of the decision variables are integer, then the LP model is named a mixed integer linear programming (MILP) model. The LP model developed in this treatise is an ILP model.

Many managerial planning and decision problems involving choices between alternatives require that "yes-no", or "go-no-go" decisions be made regarding the alternatives. Capital budgeting, plant location, critical path scheduling with resource constraints, are among such decision problems. The art and science of linear programming have developed the techniques for formulating such decision problems as ILP problems. The decision variables Xj of such problems are invariably subject to the requirement that:

$$X_j = \begin{cases} 1 & \text{if alternative } j \text{ is chosen} \\ 0 & \text{otherwise.} \end{cases}$$

The decision variables of the model developed in the present investigation are constrained to be "zero or one" only. Decision variables of this type are oftentimes called "zero-one" variables. Furthermore, the name "dummy" variables (66) is frequently used to emphasize the fact that these variables serve only as indicators as to whether or not particular alternatives are chosen or rejected.

CHAPTER V

MODEL VALIDATION

The model formulation presented in Chapter IV is now applied to the operations of an actual precast concrete systems building company, the Progressive Concrete Company (PCC). Since the model is being adapted to an already existing precast concrete systems building company, only those operational constraints which are relevant to the operational circumstances of the PCC are included in the formulated model.

A table of functional groups and their respective precast concrete components as they exist in the PCC is first presented. This presentation is then followed by a formulation of all distinct building alternatives.

Functional Groups and Precast Concrete Components

There are seven functional groups which are used by the PCC. Only five of the seven functional groups have at least two precast concrete components. Members of groups six and seven shown in Table II do not contain more than one precast concrete component and will not be used in the present validation analysis.

TABLE II

FUNCTIONAL GROUPS AND THEIR PRECAST CONCRETE COMPONENTS

Functional Group No.	Functional Group Name	Precast Concrete Components
1	Wall	Double Tee Wall Panel, Flat Wall Panel, Blocks and Accessories
2	Floor	Double Tee Floor Slab, Flat Floor Slab
3	Beam	L-Beam, Rectangular Beam
4	Center Core	Core Wall Panel, Core Box
5	Roof	Double Tee Roof Slab, Flat Roof Slab
6	Stair Landing	Stair Landing
7	Stair Frame	Stair Frame

The following symbols will be used to represent the precast concrete components which make up a building alternative

DTWP = Double Tee Wall Panel

FWP = Flat wall panel

CB = Concrete Blocks, Concrete Block Beams, and Columns which are used with block walls

DTFS = Double Tee Floor Slab

FFS = Flat Floor Slab

LB = L-Beam

RB = Rectangular Beam

CW = Central Core Wall Panel

BOX = Central Core Box

DTRS = Double Tee Roof Slab

FRS = Flat Roof Slab

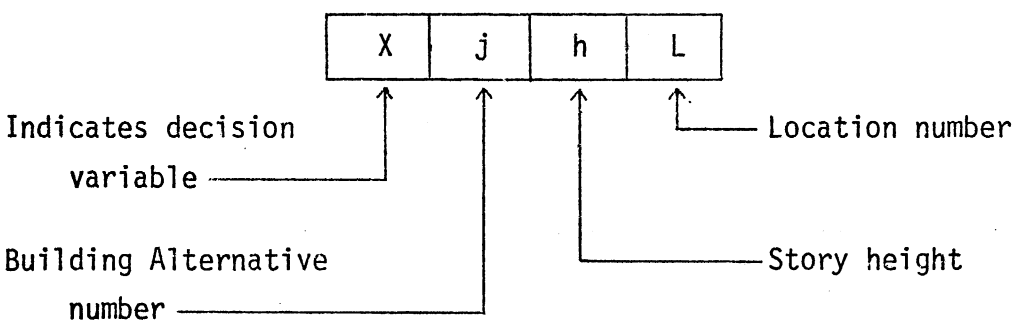
SL = Stair Landing

SF = Stair Frame

There are a total of (3)(2)(2)(2)(2) = 48 building alternatives. All the building alternatives and their relevant precast concrete components are presented in Table III.

Decision Variables Representation

A decision variable is a building alternative which has been identified by its story height and location. A typical notation for a decision variable is shown below.



For the decision variable $X_j hL$

$j = 1, 2, \ldots, 48$

= The serial number shown in Table III, of the building alternative from which the decision variable was formulated.

h = Story height of the building alternative from which the decision variable was formulated.

$= 1, 2, \ldots, 5.$

TABLE III

BUILDING ALTERNATIVES AND THEIR RELEVANT PRECAST CONCRETE COMPONENTS

Building Alternative	Relevant Precast Concrete Components	Building Alternative	Relevant Precast Concrete Components
X1	DTWP, DTFS, LB, CW, DTRS	X25	DTWP, DTFS, LB, CW, FRS
X2	DTWP, DTFS, LB, BOX, DTRS	X26	DTWP, DTFS, LB, BOX, FRS
X3	DTWP, DTFS, RB, CW, DTRS	X27	DTWP, DTFS, RB, CW, FRS
X4	DTWP, DTFM, RB, BOX, DTRS	X28	DTWP, DTFS, RB, BOX, FRS
X5	DTWP, FFS, LB, CW, DTRS	X29	DTWP, FFS, LB, CW, FRS
X6	DTWP, FFS, LB, BOX, DTRS	X30	DTWP, FFS, LB, BOX, FRS
X7	DTWP, FFS, RB, CW, DTRS	X31	DTWP, FFS, RB, CW, FRS
X8	DTWP, FFS, RB, BOX, DTRS	X32	DTWP, FFS, RB, BOX, FRS
X9	FWM, DTFS, LB, CW, DTRS	X33	FWP, DTFS, LB, CW, FRS
X10	FWP, DTFS, LB, BOX, DTRS	X34	FWP, DTFS, LB, BOX, FRS
X11	FWP, DTFS, RB, CW, DTRS	X35	FWP, DTFS, RB, CW, FRS
X12	FWP, DFFS, RB, BOX, DTRS	X36	FWP, DTFS, RB, BOX, FRS
X13	FWP, FFS, LB, CW, DTRS	X37	FWP, FFS, LB, CW, FRS
X14	FWP, FFS, LB, BOX, DTRS	X38	FWP, FFS, LB, BOX, FRS
X15	FWP, FFS, RB, CW, DTRS	X39	FWP, FFS, LB, CW, FRS
X16	FWP, FFS, RB, BOX, DTRS	X40	FWP, FFS, RB, BOX, FRS
X17	CB, DTFS, LB, CW, DTRS	X41	CB, DTFS, LB, CW, FRS
X18	CB, DTFS, LB, BOX, DTRS	X42	CB, DTFS, LB, BOX, FRS
X19	CB, DTFS, RB, CW, DTRS	X43	CB, DTFS, RB, CW, FRS
X20	CB, DTFS, RB, BOX, DTRS	X44	CB, DTFS, RB, BOX, FRS
X21	CB, FFS, LB, CW, DTRS	X45	CB, FFS, LB, CW, FRS
X22	CB, FFS, LB, BOX, DTRS	X46	CB, FFS, LB, BOX, FRS
X23	CB, FFS, RB, CW, DTRS	X47	CB, FFS, RB, CW, FRS
X24	CB, FFS, RB, BOX, DTRS	X48	CB, FFS, RB, BOX, FRS

L = location of the building alternative

= 1, 2, 3.

The relationship between the location, L, of a building alternative and the distance in miles of that building alternative from the PCC's precast concrete plant is shown in Table IV.

TABLE IV

RELATIONSHIP BETWEEN THE LOCATION, L, AND THE DISTANCE IN MILES OF A BUILDING ALTERNATIVE

Location, L.	Distance in Miles of a Building Alternative From the PCC's Precast Concrete Plant
1	75
2	150
3	225

A decision variable designated as X4543 denotes a serial number of 45 as shown in Table III, is four stories tall, and 225 miles away from the PCC's precast concrete plant.

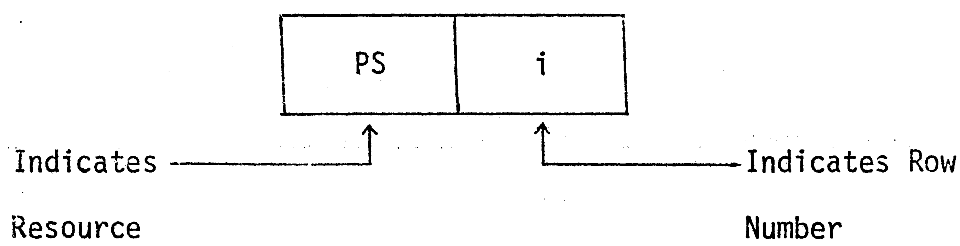
Since there are two precast concrete components which are used in the construction of floors, and since the floors of one story building alternatives are on grade, it follows that there are

48 x 5 x 3 - 3 x 24 decision variables,

= 648 decision variables to be used in the model validation.

Row Names Representation

The objective function row and the constraint constant for every constraint function is given a definite name. These names denote the type of resource the constraint constants designate and also the serial numbers of the constraint rows in which the constants are represented. However, the objective function row named "COST", has no serial row number attached to it. A typical designation of a row name or a constraint constant is shown below.



In the above designation, PS denotes prestressing steel tendons with i=1. This implies that constraint row No.1 or constraint equation No.1 is based on prestressing steel tendons and is designated as PS1. A complete listing of all the row names used in the model are listed in Table V.

There are a total of 14 rows used in the model as shown in Table V. However, all, except the first row, the objective function row, represent the constraint equations or inequalities.

Table V could be expanded more than its present length. There should be a constraint row for every distinct resource used by the concrete company whose operational data are being used to validate

TABLE V

ROW NAMES AND THE RESOURCES THEY REPRESENT

Row Name	Type of Resource Represented in the Row	Constraint Equation No.
COST	Objective Function	None
PS1	Prestressing Steel Tendons	1
RB2	Reinforcing Steel Bars	2
WM3	Wire Mesh Type I	3
WM4	Wire Mesh Type II	4
WM5	Wire Mesh Type III	5
CN6	Concrete Type I	6
CN7	Concrete Type II	7
CN8	Concrete Type III	8
PL9	Plant Labor	9
EL10	Erection Labor for Concrete Components other than Block Walls	10
ELB11	Erection Labor for Concrete Block Walls	11
WLR12	Weight Limit Requirement, in Truck Loads	12
CR13	Choice Requirements	13

the model. Furthermore, all other operational constraints which are known to affect the plant, transportation, and erection operations of the company, should be represented by a distinct constraint row as shown in Table V. All resources or constraints pertaining to the PCC's operations are listed in Table V.

Decision Variable Coefficient Computation

There are three types of decision variable coefficients involved in the model validation. The first type includes the objective function coefficients and the constraint function coefficients. The Weight Limit Requirement (WLR12) and the Choice Requirement (CR13) constraint function coefficients are excluded from coefficients of the first type for several reasons. Decision variable coefficients of the first type are computed by the direct summation of the amounts of the resources associated with the precast concrete components which constitute the decision variable. The coefficients of the decision variables for the Weight Limit Constraint (WLR12) belong to the second type of coefficients. The type three coefficients of decision variables pertain to the Choice Requirement (CR13) constraint. They are computed simply by assigning a value of one to each of them.

The following is a typical example of how the decision variable coefficients of the first type are computed using prestressing steel tendons, PS1 and the usual plan dimensions (108 feet by 108 feet) of the PCC's concrete systems building. The material quantities for prestressing steel tendons are now computed. The data for this and other computations of decision variable coefficients are obtained from Table X in Appendix A.

Perimeter of building	=	4 (108 feet - 0 inch)
	=	432 feet - 0 inch
Width of DTWP	=	8 feet - 0 inch
Perimeter Length per DTWP, allowing 3' - 0" for windows	=	8 feet - 0 inch + 3 feet - 0 inch
	=	11 feet - 0 inch
Therefore DTWP/story height	=	432 ÷ 11 panels
	=	39.273 panels
	=	40 panels/story
Story height - floor to floor	≐	12 feet, using L-Beams
	=	14 feet, using Rectangular Beams
Total length of DTWP/story height	=	40 x 12 feet (for 12 feet wall height)
	=	480 feet
		or
	=	40 x 14 feet (for 14 feet wall height)
	=	560 feet/story

Flat Wall Panel (FWP)

A similar computation for FWP is also made to obtain the total length of FWP per story height.

Hence:

Total length of FWP = 432 feet, using L-Beams

= 504 feet, using Rectangular Beams.

For every other constraint equation (function), a table similar to

Table VI is computed and presented in Tables XI through XXI in Appendix B. In Table VI and in the tables in Appendix B, if two quantities of a given resource are tabulated for a precast concrete component and a story height, the upper quantity stands for a 12 feet wall height, while the lower quantity represents the quantity for a 14 feet wall height. A value of zero in Table VI and in all the tables of Appendix B implies that the precast concrete component does not use prestressing steel tendons or the particular resource at the indicated floor (story height), or not at all. The units of the quantities of each type of resource are stated in each table.

The computation of the coefficient of a decision variable for the constraint equation PS1 is now illustrated, using the data from the column headed "1st Floor" in Table VI and the information in Table III. For the decision variable X1411, we establish from Table III that X14 is composed of FWP, FFS, LB, BOX, DTRS. When the lengths of prestressing steel tendons used in the precast components that constitute X14 are added the following can be obtained:

$$\sum_{k=1}^{kk} M_k(i,j) = \sum_{k=1}^{3} M_k(1,14)$$

$$= 388 + 0 + 2160 + 0 + 5488$$

$$= 11536 \text{ feet, where}$$

$M_k(i,j)$ = quantity (feet) of the material (prestressing steel tendons-PS) i, required to build the relevant precast concrete component k, in a decision variable j (=14 in this example).

kk = total number of relevant precast concrete

TABLE VI

PRESTRESSING STEEL REQUIREMENTS (PSI)

Member Description	Quantities Feet Consumed Per Floor				
	1st Floor	2nd Floor	3rd Floor	4th Floor	5th Floor
(1) Double Tee Wall Panels	4800 / 5600	9600 / 11200	14400 / 16800	19200 / 22400	24000 / 28000
(2) Flat Wall Panels	3888 / 4536	7776 / 9072	11664 / 13608	1552 / 18144	19440 / 22680
(3) Block and Block Beams	0	0	0	0	0
(4) Columns to go with Blocks	1920 2240	3840 4480	5760 6720	7680 8960	9600 11200
(5) Double Tee Floor Members	0	8232	16464	24696	32928
(6) Flat Floor Slabs	0	16464	32928	49392	65856
(7) L-Beams	2160	4320	6480	8640	10800
(8) Rectangular Beams	2160	4320	6480	8640	10800
(9) Core Wall Panels	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0
(10) Boxes for Ser. Core	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0
(11) Double Tee Roof Members	5488	5488	5488	5488	5488
(12) Flat Roof Slabs	13720	13720	13720	13720	13720

components in the decision variable j, utilizing the material i.

= 3 in this illustration.

Since $\sum_{k=1}^{kk} M_k\ (i, j) = 11536$, the coefficient of X1411 in the constraint row PS1 is 11536. This is the procedure used to compute all the coefficients of the first type both in the objective function and in the constraint equations.

General Requirements for Decision Variable Coefficients

There are two criteria which must be satisfied by every term in a constraint equation or in the objective function expression:

1. Every coefficient of a decision variable in a constraint equation must be capable of direct conversion into cost by multiplying such a coefficient by a constant numerical quantity which may be unique for each constraint equation.
2. The terms in a constraint equation or in the objective function must be dimensionally homogeneous. This criterion demands that the product of a decision variable and its coefficient for any specified constraint equation be expressed in precisely the same dimensions as the dimensions of the resource quantity on the right hand side of the constraint equation. In the case of objective function terms, each product must be numerically equal to a value of United States dollars.

The transportation of different precast concrete components along the highway is affected differently by highway use requirements. Thus a particular truck used to transport different precast concrete components may be considered fully loaded either because of its gross weight or because of the total height of the truck and its load. Other load characteristics can also be the constraining requirements in various realistic circumstances. According to the PCC's transportation arrangements, every precast concrete component, except concrete blocks and center service core boxes, costs $50 to transport and every truck load costs one dollar per truck load per mile. Thus a truck load of one type of precast concrete component may not cost the same amount of dollars as a truck load of a different type of precast concrete component. These cost differences are illustrated in Figures 4, 5, and 6.

In order to ensure that the decision variable coefficients in the constraint equation pertaining to truck loads (the weight limit constraint WLR12), have the same unit cost, it has been necessary to convert every coefficient in the WLR12 constraint onto the same cost basis by using a conversion factor.

At every location the conversion factor for a truck load of a particular precast concrete component is unique. It is affected by the following:

1. The distance of travel or location, since every truck load of every type of precast concrete component, except concrete blocks, costs one dollar per mile.
2. The number of pieces of precast concrete components per truck load.
3. The cost of that truck load which costs the least for a given location.

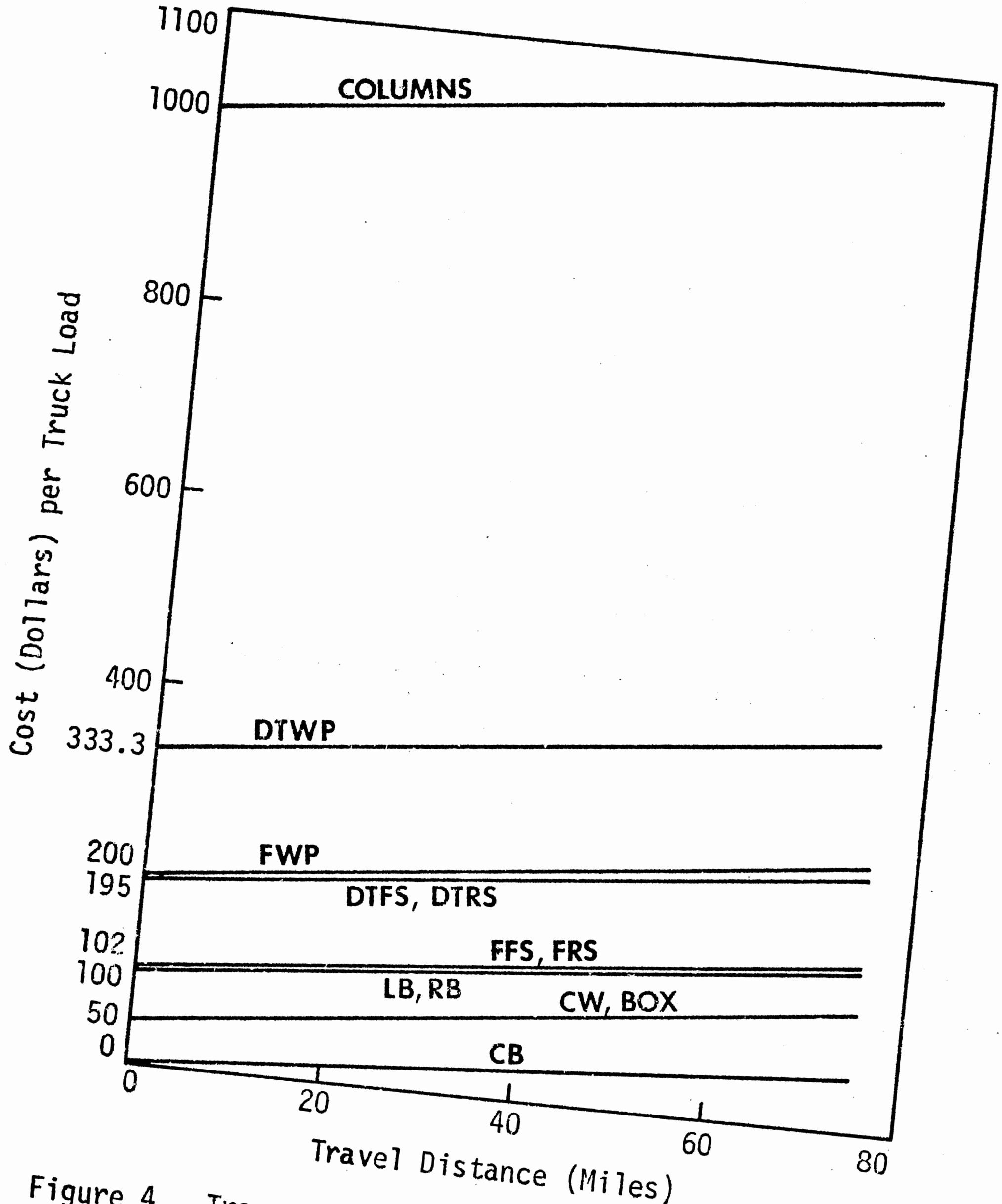


Figure 4. Transportation Cost of Different Precast Concrete Components for the First 75 Miles from the Precasting Plant

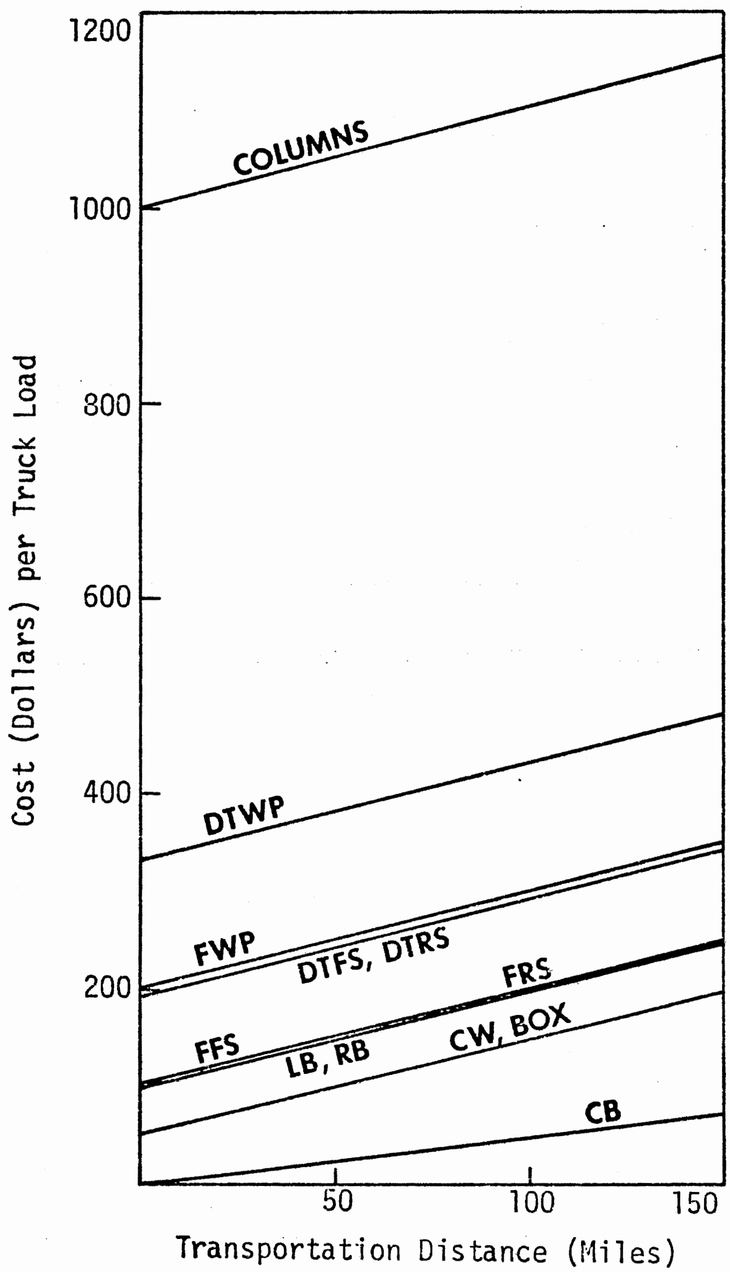


Figure 5. Transportation Cost of Different Precast Concrete Components for the First 150 Miles from the Precasting Plant

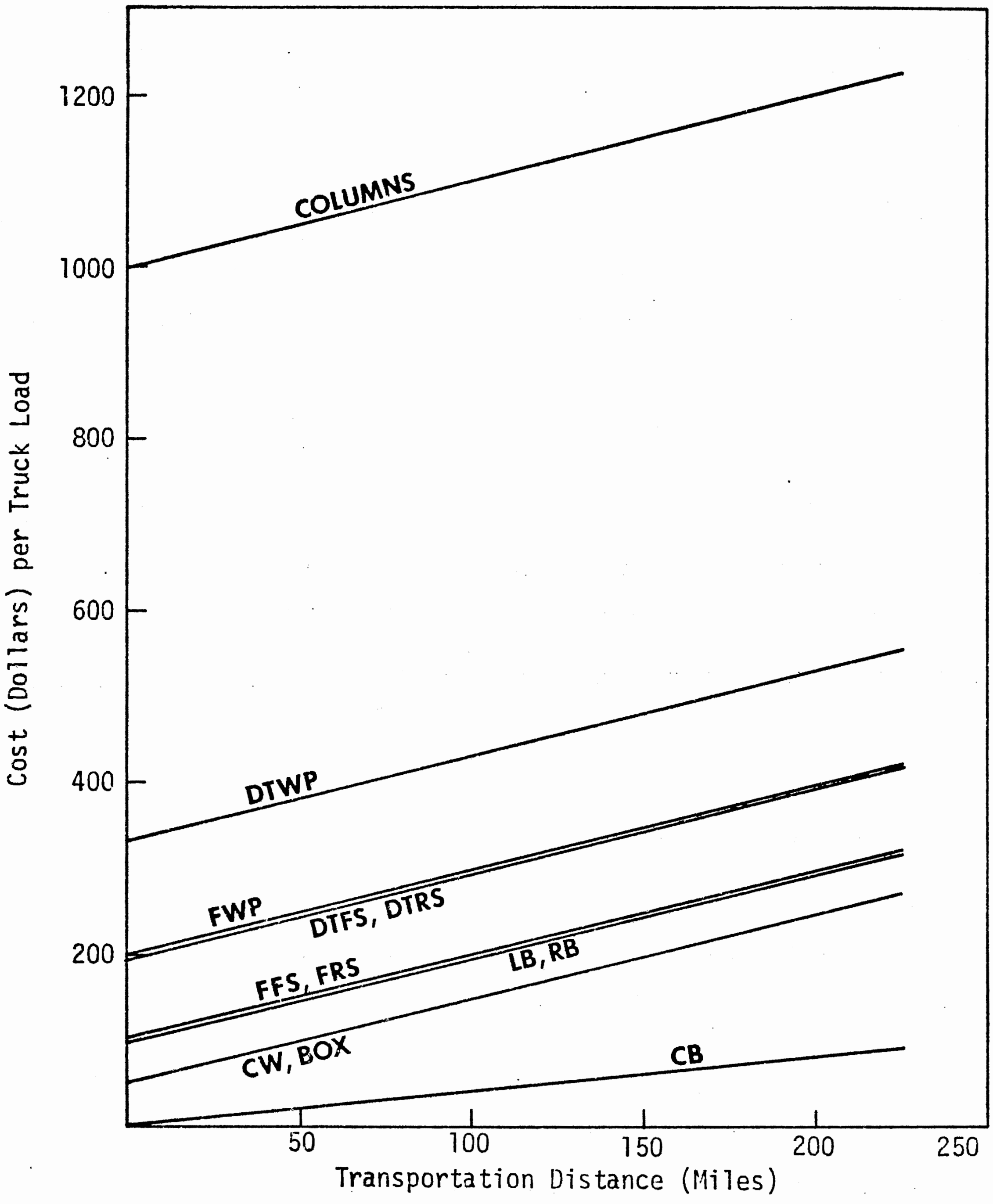


Figure 6. Transportation Cost of Different Precast Concrete Components for the First 225 Miles from the Precasting Plant

Once the conversion factor has been applied to the truck loads of every type of precast concrete component, the decision variable coefficients of the second type can then be computed.

Computation of Conversion Factors for Truck Loads at First Location

The conversion factors for a typical location are computed by establishing the total number of truck loads and the total transportation cost for each type of precast concrete component to that location. The total transportation cost is then divided by the number of truck loads to obtain the cost per truck load. This computation is made for each type of precast concrete component. The least cost per truck load is used as a basis for comparison to establish the conversion factors.

Hence, the conversion factor CFi for a precast concrete component i at a specified location is stated mathematically as follows:

$$CFi = \frac{CTLi}{LCTL}, \text{ where}$$

CTLi = the cost per truck load of precast concrete component i at a specified location.

LCTL = the least cost per truck load up to the specified location.

It should be noted that CFi = 1 if the cost per truck load of precast component i is the least cost per truck load at the particular location. The results of these computations for the first location are presented in Table VII. Where two values are tabulated in any one column in Table VII and Table VIII, the upper value refers to 12 feet tall wall

TABLE VII

SUMMARY OF COMPUTATION OF CONVERSION FACTORS FOR THE FIRST LOCATION

Precast Concrete Component	Total Transportation Cost, 1st Story	Truck Loads Before Conversion for 1st Story	Cost Per Truck Load	Conversion Factor	Converted Truck Load
Double Tee Wall Panel	$2450 / $2525	6 / 7	$408.33 / $360.71	6.842 / 6.044	41 / 43
Flat Wall Panel	$2475 / $2475	4 / 4	$275.00 / $275.00	4.61	19 / 19
Concrete Block	$357.98 / $417.76	6 / 7	$59.63 / $59.68	1 / 1	6 / 7
Columns to go with Block	$2150	2	$1075	18	36
Double Tee Floor Member	$2700	10	$270	4.524	46
Flat Floor Slab	$3375	19	$177.63	2.976	57
L-Beam	$525	3	$175	2.932	9
Rectangular Beam	$525	3	$175	2.932	9
Core Wall Panel	$500	4	$125	2.095	9
Box	$500	4	$125	2.095	9
Double Tee Roof Member	$2700	10	$270	4.524	46
Flat Roof Slab.	$3375	19	$177.63	2.976	57

TABLE VIII

SUMMARY OF CONVERSION FACTORS AND CONVERTED TRUCK LOADS FOR THE FIRST, SECOND, AND THIRD LOCATIONS

Precast Concrete Component	Conversion Factors			Conversion Factors		
	1st Location	2nd Location	3rd Location	1st Location	2nd Location	3rd Location
Double-Tee Wall Panel	6.842 / 6.044	6.36 / 5.73	6.07 / 5.55	41 / 43	39 / 41	37 / 39
Flat Wall Panel	4.61 / 4.61	4.61 / 4.61	4.62 / 4.62	42 / 42	42 / 42	42 / 42
Concrete Block	1 / 1	1 / 1	1 / 1	6 / 7	6 / 7	6 / 7
Column With Block	18	15.13	13.32	36	31	27
Double-Tee Floor Member	4.52	4.54	4.57	46	46	46
Flat Floor Slab	2.98	3.32	3.56	57	64	68
L-Beam	2.93	3.29	3.53	9	10	11
Rectangular Beam	2.93	3.29	3.53	9	10	11
Core Wall Panel	2.09	2.63	2.99	9	11	12
Core Service Box	2.09	2.63	2.99	9	11	12
Double Tee Roof Member	4.52	4.54	4.57	46	46	46
Flat Roof Slab	2.98	3.32	3.56	57	64	68

while the lower value is for the 14 feet tall wall. Conversion factors for all three locations are summarized in Table VIII. The data used to compute the conversion factors for the second and third locations are presented in Appendix C.

The Need for Solving the Problem by Many ILP Models

During the verification of the ILP model developed in this treatise, 648 distinct decision variables were formulated. Because of the following reasons, it was necessary to divide the model into 15 distinct models corresponding to 15 categories of buildings.

1. Each of the 15 categories of buildings corresponds to a specific story height at a specific location.
2. Construction materials used in different story heights did not vary linearly from one-story-tall buildings to five-story-tall buildings. This non-linear relationship is illustrated in Figure 8.

Computerized Solution to the Linear Programming Models

The IBM (International Business Machines) computer program package, MPSX360 (Mathematical Programming Systems Extended-360) provided the computerized solutions to the 15 LP models (67, 68). The MPSX360 program package solved each of the 15 ILP model problems in two stages. In the first stage, all the decision variables were assumed to be non-integer (continuous). The problems were then solved using the Revised Simplex Method. Many texts on linear programming by Dantzig (3),

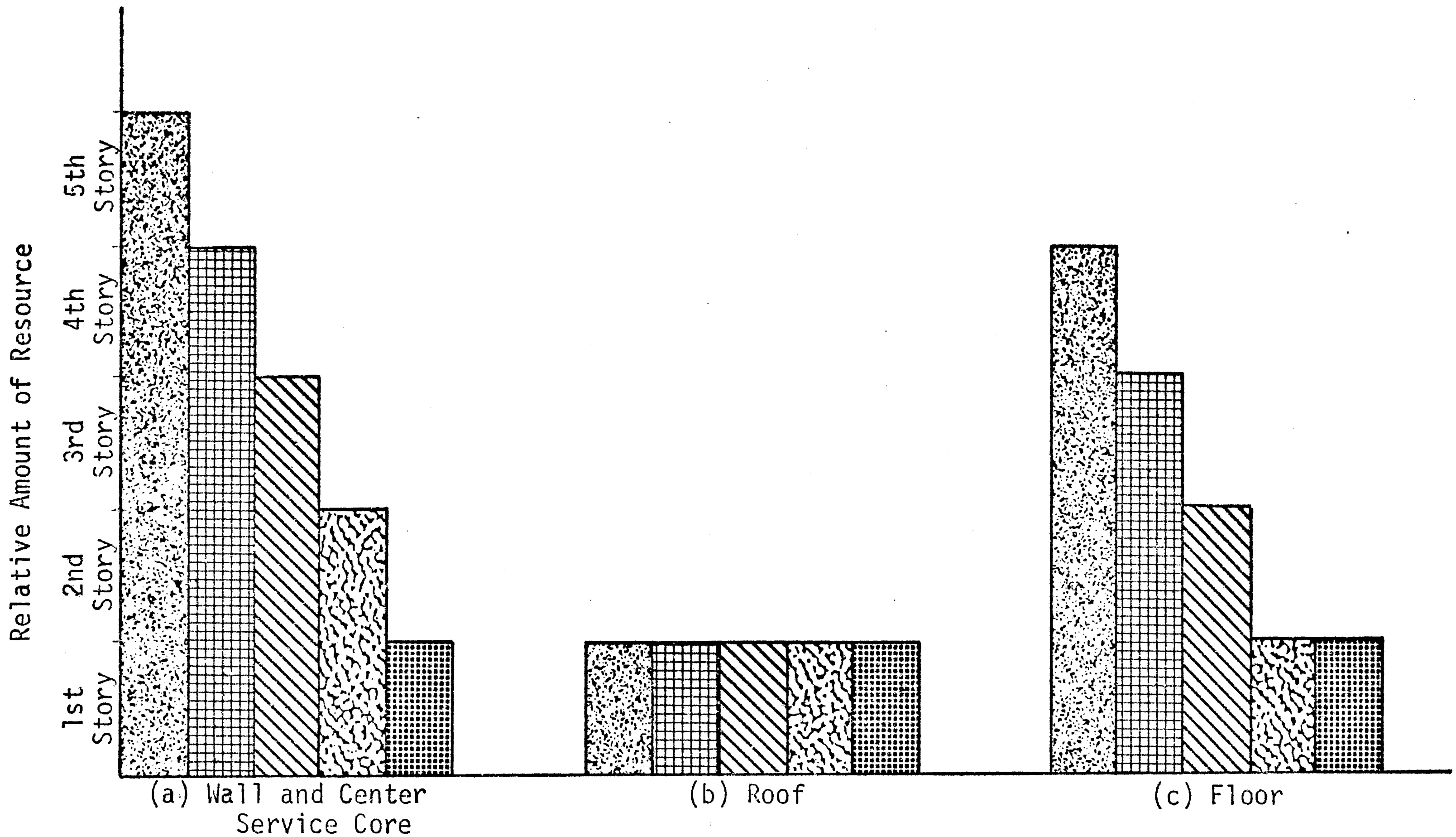


Figure 7. Rate of Consumption of a Typical Resource by Functional Groups

Locks (66), and Zionts (69) have good illustrative problems on the Revised Simplex Method. In the second stage of the solution process, a method, the Branch and Bound algorithm, was used to obtain an integer solution from the solution of the first stage.

The Branch and Bound algorithm was introduced by Land and Doig (70). Again the texts on linear programming by Dantzig (3), Locks (66), Zionts (69), Wagner (71), have good examples on the Branch and Bound algorithm.

CHAPTER VI

SELECTION AND RANKING OF OPTIMAL COMBINATIONS

The objective of the analysis was to select the best building alternatives for each category of building. In the process, linear programming was used in such a way as to provide information on the relative desirability of different combinations, and to rank them for planning purposes.

For each of the 15 categories of buildings (combinations of specified story heights up to five story heights, plus a distance from the plant: up to 75 miles, 75-150 miles, 150-225 miles), LP models to select optimum combinations of precast concrete components which make up building alternatives (combinations of relevant precast concrete components, with one type of relevant precast concrete component from each of the seven functional groups), were solved in two stages. In the first stage, three alternatives were obtained as the best choices for that category by using a linear programming model which allowed the selection of up to three building alternatives. Since the objective of the project is to obtain optimal combinations of precast concrete components and to establish the relative desirability of the combinations, further uses were made with a model which restricted the choice to one. It was necessary to choose three optimal alternatives for each of the 15 categories of buildings because in some cases, a feasible linear programming model allowing the choice of one building alternative could not be found.

In the "best three" runs, for each of the 12 constraint functions, the right hand side (RHS) constraint constants which set limitations on Prestressing Steel Tendons, Reinforcing Steel Bars, etc., were set at such levels as would permit up to three choices of alternatives. For the "best one" runs, the RHS constants were set so that only one alternative is feasible. Thus both the lower and upper limits for the RHS constants in the "best three" models are approximately three times as large as they are in the "best one" models. Three "best one" models were solved for each of the 15 categories of buildings, to make the further ranking of "best" (1^{st} choice), "second best" (2^{nd} choice) and "third best" (3^{rd} choice). In general, it was found that only the "best" (1^{st} choice) alternatives were relevant, and the second and third choices were insignificant.

In this chapter, the results of all the 60 computer runs are presented. First, the "best three" choices for each of the 15 categories of buildings are shown in Figures 8 through 13. Following these is Table IX which contains a summary of all the "best three" and all the "best", "second best" and "third best" building alternatives, and the precast concrete components which constitute them.

The building alternatives X1, X2, X26 were the only combinations which were members of the 1^{st} choices for all of the 60 runs.

Optimal Concrete Components Recommended for Concrete Systems Buildings Development

It is significant to note that certain geometrical shapes are

NODE	2
FUNCTIONAL	150024.0000
ESTIMATION	INTEGER
15= X0111	1.0000
16= X0211	1.0000
17= X0311	.
18= X0411	.
19= X0911	.
20= X1011	.
21= X1111	.
22= X1211	.
23= X1711	.
24= X1811	.
25= X1911	.
26= X2011	.
27= X2511	.
28= X2611	1.0000
29= X2711	.
30= X2811	.
31= X3311	.
32= X3411	.
33= X3511	.
34= X3611	.
35= X4111	.
36= X4211	.
37= X4311	.
38= X4411	.

(a) First Location

NODE	1
FUNCTIONAL	151565.0000
ESTIMATION	INTEGER
15= X0112	1.0000
16= X0212	1.0000
17= X0312	.
18= X0412	.
19= X0912	.
20= X1012	.
21= X1112	.
22= X1212	.
23= X1712	.
24= X1812	.
25= X1912	.
26= X2012	.
27= X2512	.
28= X2612	1.0000
29= X2712	.
30= X2812	.
31= X3312	.
32= X3412	.
33= X3512	.
34= X3612	.
35= X4112	.
36= X4212	.
37= X4312	.
38= X4412	.

(b) Second Location

NODE	5
FUNCTIONAL	158574.0000
ESTIMATION	INTEGER
15= X0113	1.0000
16= X0213	1.0000
17= X0313	.
18= X0413	.
19= X0913	.
20= X1013	.
21= X1113	.
22= X1213	.
23= X1713	.
24= X1813	.
25= X1913	.
26= X2013	.
27= X2513	.
28= X2613	1.0000
29= X2713	.
30= X2813	.
31= X3313	.
32= X3413	.
33= X3513	.
34= X3613	.
35= X4113	.
36= X4213	.
37= X4313	.
38= X4413	.

(c) Third Location

Figure 8. Selection of the Three Most Optimal Combinations for the First Story Height at Three Locations

NODE	1
FUNCTIONAL	304360.0000
ESTIMATION	INTEGER
15= X0121	1.0000
16= X0221	1.0000
17= X0321	.
18= X0421	.
19= X0521	.
20= X0621	.
21= X0721	.
22= X0821	.
23= X0921	.
24= X1021	.
25= X1121	.
26= X1221	.
27= X1321	.
28= X1421	.
29= X1521	.
30= X1621	.
31= X1721	.
32= X1821	.
33= X1921	.
34= X2021	.
35= X2121	.
36= X2221	.
37= X2321	.
38= X2421	.
39= X2521	.
40= X2621	1.0000
41= X2721	.
42= X2821	.
43= X2921	.
44= X3021	.
45= X3121	.
46= X3221	.
47= X3321	.
48= X3421	.
49= X3521	.
50= X3621	.
51= X3721	.
52= X3821	.
53= X3921	.
54= X4021	.
55= X4121	.
56= X4221	.
57= X4321	.
58= X4421	.
59= X4521	.
60= X4621	.
61= X4721	.
62= X4821	.

(a) First Location

NODE	93
FUNCTIONAL	334773.0000
ESTIMATION	INTEGER
15= X0123	.
16= X0223	1.0000
17= X0323	.
18= X0423	.
19= X0523	.
20= X0623	.
21= X0723	.
22= X0823	.
23= X0923	.
24= X1023	.
25= X1123	.
26= X1223	.
27= X1323	.
28= X1423	.
29= X1523	.
30= X1623	.
31= X1723	.
32= X1823	.
33= X1923	.
34= X2023	.
35= X2123	.
36= X2223	.
37= X2323	.
38= X2423	.
39= X2523	.
40= X2623	.
41= X2723	.
42= X2823	.
43= X2923	1.0000
44= X3023	1.0000
45= X3123	.
46= X3223	.
47= X3323	.
48= X3423	.
49= X3523	.
50= X3623	.
51= X3723	.
52= X3823	.
53= X3923	.
54= X4023	.
55= X4123	.
56= X4223	.
57= X4323	.
58= X4423	.
59= X4523	.
60= X4623	.
61= X4723	.
62= X4823	.

(b) Third Location

Figure 9. Selection of the Three Most Optimal Combinations up to the Second Story Height at Two Locations

INTEGER NODES

NODE	4	100	110
FUNCTIONAL	317437.0000	316777.0000	316777.0000
ESTIMATION	INTEGER	INTEGER	INTEGER
15= X0122	.	1.0000	1.0000
16= X0222	1.0000	.	1.0000
17= X0322	1.0000	1.0000	.
18= X0422	.	.	.
19= X0522	.	.	.
20= X0622	1.0000	.	.
21= X0722	.	.	.
22= X0822	.	.	.
23= X0922	.	.	.
24= X1022	.	.	.
25= X1122	.	.	.
26= X1222	.	.	.
27= X1322	.	.	.
28= X1422	.	.	.
29= X1522	.	.	.
30= X1622	.	.	.
31= X1722	.	.	.
32= X1822	.	.	.
33= X1922	.	.	.
34= X2022	.	.	.
35= X2122	.	.	.
36= X2222	.	.	.
37= X2322	.	.	.
38= X2422	.	.	.
39= X2522	.	.	.
40= X2622	.	1.0000	.
41= X2722	.	.	1.0000
42= X2822	.	.	.
43= X2922	.	.	.
44= X3022	.	.	.
45= X3122	.	.	.
46= X3222	.	.	.
47= X3322	.	.	.
48= X3422	.	.	.
49= X3522	.	.	.
50= X3622	.	.	.
51= X3722	.	.	.
52= X3822	.	.	.
53= X3922	.	.	.
54= X4022	.	.	.
55= X4122	.	.	.
56= X4222	.	.	.
57= X4322	.	.	.
58= X4422	.	.	.
59= X4522	.	.	.
60= X4622	.	.	.
61= X4722	.	.	.
62= X4822	.	.	.

Figure 10. Selection of the Three Most Optimal Combinations up to the Second Story Height at the Second Location

NODE	1
FUNCTIONAL	463243.0000
ESTIMATION	INTEGER
15= X0131	1.0000
16= X0231	.
17= X0331	.
18= X0431	.
19= X0531	.
20= X0631	.
21= X0731	.
22= X0831	.
23= X0931	.
24= X1031	.
25= X1131	.
26= X1231	.
27= X1331	.
28= X1431	.
29= X1531	.
30= X1631	.
31= X1731	.
32= X1831	.
33= X1931	.
34= X2031	.
35= X2131	.
36= X2231	.
37= X2331	.
38= X2431	.
39= X2531	1.0000
40= X2631	1.0000
41= X2731	.
42= X2831	.
43= X2931	.
44= X3031	.
45= X3131	.
46= X3231	.
47= X3331	.
48= X3431	.
49= X3531	.
50= X3631	.
51= X3731	.
52= X3831	.
53= X3931	.
54= X4031	.
55= X4131	.
56= X4231	.
57= X4331	.
58= X4431	.
59= X4531	.
60= X4631	.
61= X4731	.
62= X4831	.

(a) First Location

NODE	4
FUNCTIONAL	480385.0000
ESTIMATION	INTEGER
15= X0132	1.0000
16= X0232	1.0000
17= X0332	.
18= X0432	.
19= X0532	.
20= X0632	.
21= X0732	.
22= X0832	.
23= X0932	.
24= X1032	.
25= X1132	.
26= X1232	.
27= X1332	.
28= X1432	.
29= X1532	.
30= X1632	.
31= X1732	.
32= X1832	.
33= X1932	.
34= X2032	.
35= X2132	.
36= X2232	.
37= X2332	.
38= X2432	.
39= X2532	.
40= X2632	.
41= X2732	.
42= X2832	.
43= X2932	.
44= X3032	1.0000
45= X3132	.
46= X3232	.
47= X3332	.
48= X3432	.
49= X3532	.
50= X3632	.
51= X3732	.
52= X3832	.
53= X3932	.
54= X4032	.
55= X4132	.
56= X4232	.
57= X4332	.
58= X4432	.
59= X4532	.
60= X4632	.
61= X4732	.
62= X4832	.

(b) Second Location

NODE	4
FUNCTIONAL	467343.0000
ESTIMATION	INTEGER
15= X0133	1.0000
16= X0233	.
17= X0333	.
18= X0433	.
19= X0533	.
20= X0633	.
21= X0733	.
22= X0833	.
23= X0933	.
24= X1033	.
25= X1133	.
26= X1233	.
27= X1333	.
28= X1433	.
29= X1533	.
30= X1633	.
31= X1733	.
32= X1833	.
33= X1933	.
34= X2033	.
35= X2133	.
36= X2233	.
37= X2333	.
38= X2433	.
39= X2533	1.0000
40= X2633	1.0000
41= X2733	.
42= X2833	.
43= X2933	.
44= X3033	.
45= X3133	.
46= X3233	.
47= X3333	.
48= X3433	.
49= X3533	.
50= X3633	.
51= X3733	.
52= X3833	.
53= X3933	.
54= X4033	.
55= X4133	.
56= X4233	.
57= X4333	.
58= X4433	.
59= X4533	.
60= X4633	.
61= X4733	.
62= X4833	.

(c) Third Location

Figure 11. Selection of the Three Most Optimal Combinations up to the Third Story Height at Three Locations

NODE	13
FUNCTIONAL	623413.0000
ESTIMATION	INTEGER
15= X0141	1.0000
16= X0241	1.0000
17= X0341	.
18= X0441	.
19= X0541	.
20= X0641	.
21= X0741	.
22= X0841	.
23= X0941	.
24= X1041	1.0000
25= X1141	.
26= X1241	.
27= X1341	.
28= X1441	.
29= X1541	.
30= X1641	.
31= X1741	.
32= X1841	.
33= X1941	.
34= X2041	.
35= X2141	.
36= X2241	.
37= X2341	.
38= X2441	.
39= X2541	.
40= X2641	.
41= X2741	.
42= X2841	.
43= X2941	.
44= X3041	.
45= X3141	.
46= X3241	.
47= X3341	.
48= X3441	.
49= X3541	.
50= X3641	.
51= X3741	.
52= X3841	.
53= X3941	.
54= X4041	.
55= X4141	.
56= X4241	.
57= X4341	.
58= X4441	.
59= X4541	.
60= X4641	.
61= X4741	.
62= X4841	.

(a) First Location

NODE	14
FUNCTIONAL	638313.0000
ESTIMATION	INTEGER
15= X0142	1.0000
16= X0242	1.0000
17= X0342	.
18= X0442	.
19= X0542	.
20= X0642	.
21= X0742	.
22= X0842	.
23= X0942	.
24= X1042	1.0000
25= X1142	.
26= X1242	.
27= X1342	.
28= X1442	.
29= X1542	.
30= X1642	.
31= X1742	.
32= X1842	.
33= X1942	.
34= X2042	.
35= X2142	.
36= X2242	.
37= X2342	.
38= X2442	.
39= X2542	.
40= X2642	.
41= X2742	.
42= X2842	.
43= X2942	.
44= X3042	.
45= X3142	.
46= X3242	.
47= X3342	.
48= X3442	.
49= X3542	.
50= X3642	.
51= X3742	.
52= X3842	.
53= X3942	.
54= X4042	.
55= X4142	.
56= X4242	.
57= X4342	.
58= X4442	.
59= X4542	.
60= X4642	.
61= X4742	.
62= X4842	.

(b) Second Location

NODE	24
FUNCTIONAL	654013.0000
ESTIMATION	INTEGER
15= X0143	1.0000
16= X0243	1.0000
17= X0343	.
18= X0443	.
19= X0543	.
20= X0643	.
21= X0743	.
22= X0843	.
23= X0943	.
24= X1043	1.0000
25= X1143	.
26= X1243	.
27= X1343	.
28= X1443	.
29= X1543	.
30= X1643	.
31= X1743	.
32= X1843	.
33= X1943	.
34= X2043	.
35= X2143	.
36= X2243	.
37= X2343	.
38= X2443	.
39= X2543	.
40= X2643	.
41= X2743	.
42= X2843	.
43= X2943	.
44= X3043	.
45= X3143	.
46= X3243	.
47= X3343	.
48= X3443	.
49= X3543	.
50= X3643	.
51= X3743	.
52= X3843	.
53= X3943	.
54= X4043	.
55= X4143	.
56= X4243	.
57= X4343	.
58= X4443	.
59= X4543	.
60= X4643	.
61= X4743	.
62= X4843	.

(c) Third Location

Figure 12. Selection of the Three Most Optimal Combinations up to the Fourth Story Height at Three Locations

FUNCTIONAL	773414.0000	FUNCTIONAL	792093.0000	FUNCTIONAL	810714.0000
ESTIMATION	INTEGER	ESTIMATION	INTEGER	ESTIMATION	INTEGER
15= X0151	1.0000	15= X0152	1.0000	15= X0153	1.0000
16= X0251	1.0000	16= X0252	1.0000	16= X0253	1.0000
17= X0351	.	17= X0352	.	17= X0353	.
18= X0451	.	18= X0452	.	18= X0453	.
19= X0551	.	19= X0552	.	19= X0553	.
20= X0651	.	20= X0652	.	20= X0653	.
21= X0751	.	21= X0752	.	21= X0753	.
22= X0851	.	22= X0852	.	22= X0853	.
23= X0951	.	23= X0952	.	23= X0953	.
24= X1051	.	24= X1052	.	24= X1053	.
25= X1151	.	25= X1152	.	25= X1153	.
26= X1251	.	26= X1252	.	26= X1253	.
27= X1351	.	27= X1352	.	27= X1353	.
28= X1451	.	28= X1452	.	28= X1453	.
29= X1551	.	29= X1552	.	29= X1553	.
30= X1651	.	30= X1652	.	30= X1653	.
31= X1751	.	31= X1752	.	31= X1753	.
32= X1851	.	32= X1852	.	32= X1853	.
33= X1951	.	33= X1952	.	33= X1953	.
34= X2051	.	34= X2052	.	34= X2053	.
35= X2151	.	35= X2152	.	35= X2153	.
36= X2251	.	36= X2252	.	36= X2253	.
37= X2351	.	37= X2352	.	37= X2353	.
38= X2451	.	38= X2452	.	38= X2453	.
39= X2551	.	39= X2552	.	39= X2553	.
40= X2651	1.0000	40= X2652	1.0000	40= X2653	1.0000
41= X2751	.	41= X2752	.	41= X2753	.
42= X2851	.	42= X2852	.	42= X2853	.
43= X2951	.	43= X2952	.	43= X2953	.
44= X3051	.	44= X3052	.	44= X3053	.
45= X3151	.	45= X3152	.	45= X3153	.
46= X3251	.	46= X3252	.	46= X3253	.
47= X3351	.	47= X3352	.	47= X3353	.
48= X3451	.	48= X3452	.	48= X3453	.
49= X3551	.	49= X3552	.	49= X3553	.
50= X3651	.	50= X3652	.	50= X3653	.
51= X3751	.	51= X3752	.	51= X3753	.
52= X3851	.	52= X3852	.	52= X3853	.
53= X3951	.	53= X3952	.	53= X3953	.
54= X4051	.	54= X4052	.	54= X4053	.
55= X4151	.	55= X4152	.	55= X4153	.
56= X4251	.	56= X4252	.	56= X4253	.
57= X4351	.	57= X4352	.	57= X4353	.
58= X4451	.	58= X4452	.	58= X4453	.
59= X4551	.	59= X4552	.	59= X4553	.
60= X4651	.	60= X4652	.	60= X4653	.
61= X4751	.	61= X4752	.	61= X4753	.
62= X4851	.	62= X4852	.	62= X4853	.

(a) First Location (b) Second Location (c) Third Location

Figure 13. Selection of the Three Most Optimal Combinations up to the Fifth Story at Three Locations

TABLE IX

SUMMARY OF SELECTIONS AND THEIR PRECAST CONCRETE COMPONENTS

Combination	No. of Times Selected as: Member of 3 together	1st Choice	2nd Choice	3rd Choice	Precast Concrete Components in the Combination
X01	14	4			DTWP, DTFS, LB, CW, DTRS
X02	12	4			DTWP, DTFS, LB, BOX, DTRS
X26	10	3	2		DTWP, DTFS, LB, BOX, FRS
X25	3		6		DTWP, DTFS, LB, CW, FRS
X03			1	3	DTWP, DTFS, RB, CW, DTRS
X04				2	DTWP, DTFM, RB, BOX, DTRS
X06				3	DTWP, FFS, LB, BOX, DTRS
X09				1	FWM, DTFS, LB, CW, DTRS
X10	3		1		FWP, DTFS, LB, BOX, DTRS
X27	1				DTWP, DTFS, RB, CW, FRS
X28	1				DTWP, DTFS, RB, BOX, FRS
X29	1			1	DTWP, FFS, LB, CW, FRS
X30			1		DTWP, FFS, LB, BOX, FRS
Totals:	45	11	11	11	

associated with the 1st choice building alternatives. For instance: DTWP, DTFS, LB, CW, BOX, DTRS, and FRS, constitute the building alternatives X1, X2, and X26.

If the PCC is to operate optimally at its present location, it is recommended that the PCC should invest in the Precast concrete forms needed to make the components in X1, X2, X26. In addition, all the precast concrete components in the functional groups 6 and 7 of Table II, which are needed in all the concrete systems buildings should also be developed.

The Problems Associated with the Solution

(1) It is possible not to obtain an integer solution for a given model, e.g.:

(a) Selection of one combination for the 1st Story at all three locations.

(b) Selection of one combination for the 2nd Story at the 1st location.

(2) The verification depends on accurate historic data. This means that someone who thoroughly understands the construction requirements must be available and able to supply the needed data.

(3) It requires computerized solution.

(4) Long hours of computations must be carried out.

The Advantages of the LP Solution

(1) It gives quantitative answers which compare well with real world experiences in the construction industry (14). It should therefore be used for managerial planning and selection of precast concrete

components for systems buildings.

(2) It is very flexible with respect to environmental or local requirements. It can be expanded to reflect practically any construction requirements at the plant, the highway and the erection site, by way of constraint equations/or inequalities.

This environmental flexibility makes it capable of resolving the contradictions among the views of experts on the economics of certain geometric shapes. It does this by providing tailor-made solutions.

(3) It is capable of up-date as the need arises, by slight changes in the computed coefficients, or by addition or deletion of constraints.

(4) The use of the models as developed does not require any in-depth knowledge of computer programming.

CHAPTER VII

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

The objective of this research was the selection of types of forms for a new plant location considering the most economical and feasible combinations of precast concrete components needed for a concrete systems building. It has shown that by use of integer linear programming, these economical and feasible combinations can be selected for a concrete systems building company and that the chosen combinations can be ranked in the order of their economic advantages. The integer linear programming model developed in the research places emphasis on the importance of environmental requirements by considering all significant requirements in the constraint equations.

The research treated precast concrete plant operations, transportation of the precast concrete components along the highway, and the erection of the components at the building site.

The feasible combinations of precast concrete components for an existing precast concrete systems building company were compared, and the most economical combinations selected for every story height and at each specified distance from the precast concrete plant to the building site. It was then recommended that those geometric shapes which consistently formed the economical combinations should be used in the company's precast concrete systems buildings.

Conclusions

The following conclusions should be made based on the findings of this research.

1. Environmental requirements for the construction of different precast concrete components affect the economics of these components in different ways. Therefore, one should not expect different precast concrete components to possess the same economic advantages, regardless of the arrangements in the precast concrete plant, and the requirements of the marketing area in which these components are to be sold.

2. Conclusions regarding the economics of any one precast concrete component at any specified environment should not be based on the economics of such an individual piece. It should be based upon the economics of those combinations of individual precast concrete components.

The results of the integer linear programming model agree well with experiences of the concrete systems building company whose operational data were used to verify the model. Of all the candidates for selection, the double-tee featured consistently as the most economical geometric shape. Thus this method of analysis should be useful for the precast concrete industry in this country.

Recommendations

The linear programming models developed in this research can be extended to cover greater story heights than the five story heights used in the model verification. Furthermore, once the most economical and feasible combination(s) have been chosen, the lengths and other physical dimensions of the selected components can be varied to establish the variation of cost with dimensional changes.

The scope of this research can also be extended to include all the design problems and costs associated with the design of each combination of precast concrete components, which is a candidate for selection. This can be achieved by relating the LP models developed in this treatise to the LP models already published in the literature on the optimal design of multistory framed structures by linear programming.

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APPENDIX A

DATA AS ORIGINALLY COLLECTED FROM THE PROGRESSIVE CONCRETE COMPANY

TABLE X

PRECAST CONCRETE COMPONENTS AND THE RESOURCES NEEDED FOR THEIR PRODUCTION AND ERECTION

	Double Tee Wall Panel	Flat Wall Panel	Columns with Blocks	Double Tee Floor Slab	Flat Floor Slab	L-Beam	Rectangular Beam	Core Wall Panel	Core Box	Double Tee Roof Slab	Stair Landing	Stair Frame	Flat Roof Slab
All Costs Associated With Plant Production	$20/lin ft	$3/sq ft	$10/lin ft	$12/lin ft	$1.80/sq ft $14.40/lin ft	$18/lin ft	$15/lin ft	$3/sq ft	$160/lin ft of building height	$10.50 /ft	$2.00 /sq ft	$15/riser riser ht, 7¾ in.	$1.50 /sq ft or $12/ft
Freight Costs	← $50/piece, $1/mile/truck load →								1 box/truck load, $50/ box + $1/ mi time load	← $50/piece, $1/mile/truck load →			
Labor at Plant--Costing, Handling	4 men /150 ft /day	7 men /1500 ft /day	2 men /4 columns /day	7 men /500 ft /day	5 men /200 ft /day	4 men /100 ft /day	3 men /100 ft /day	7 men /1200 sq ft /day	5 men /box /day	6 men /400 ft /day	2 men /100 sq ft /day	11 men /piece /day	5 men /200 ft /day
Weights	570 lb/ft	70 lb/sq ft	150 lb/ft	335 lb/ft	80 lb/sq ft	525 lb/ft	450 lb/ft	60 lb/sq ft		280 lb/ft	40 lb /sq ft	400 lb /riser	60 lb/sq ft 480 lb/ft
All Costs Associated With Erection	$125/piece	$150/piece	$80/piece	$50/piece	$75/piece	$75/piece	$75/piece	$200/piece	$150 each	$50 /piece	$60 /piece	$60 /piece	$50 /piece
Erection Labor, 1st Story	6.25 man-hrs /piece	6.5 man-hrs /piece	4.0 man-hrs /piece	2.5 man-hrs /piece	2.50 man-hrs /piece	3.75 man-hrs /piece	3.5 man-hrs /piece	10.0 man-hrs /piece	7.5 man-hrs /piece	2.5 man-hrs /piece	3.0 man-hrs /piece	3.0 man-hrs /piece	2.5 man-hrs /piece
Prestressing Steel Tendons	10 ft /ft of panel	9 ft /ft of panel	4 ft /ft of column	6 ft /ft of slab	12 ft /ft of slab	12 ft /ft of beam	12 ft /ft of beam	X*	X	4 ft /ft of slab	X	4.17 ft /riser	10 ft /ft of slab
Reinforcing Bars	X	3 lb /ft of panel	11 lb /ft of column	X	X	4 lb /ft of beam	3 lb /ft of beam	2.5 lb /sq ft of panel	25 lb /box	X	2 lb /sq ft	X	X
Wire Mesh, Type I	8 sq ft /ft of L Panel	X	X	8 sq ft /ft of slab	16 sq ft /ft of slab	X	X	X	X	8 sq ft /ft	X	4 sq ft /riser	8 sq ft /ft
Wire Mesh, Type II	2 ft /ft of panel	X	X	20 ft /slab	X	X	X	X	X	20 ft/ft	X	X	X
Wire Mesh, Type III	X	X	X	X	X	X	X	X	612 sq ft /box	X	X	X	X
Concrete, Type I	X	X	X	0.103 cri yd /ft	0.198 cri yd /ft	X	X	.019 cri yd /sq ft	1126 cri yd /box	0.090 cu yd /ft	X	.09 cu yd /riser	0.148 cu yd /ft
Concrete, Type II	0.176 cri yd /ft	0.296 cri yd /ft	0.037 cri yd /ft	X	X	0.130 cri yd /ft	0.111 cri yd /ft	X	X	X	0.012 cu yd /sq ft	X	X

*X means that the precast concrete component does not consume that particular resource.

APPENDIX B

TABLES OF QUANTITIES FOR THE CONSTRAINT EQUATIONS

TABLE XI

REINFORCING STEEL REQUIREMENTS (RB2)

Member Description	Quantities (lb) Consumed				
	Up to First Story	Up to Second Story	Up to Third Story	Up to Fourth Story	Up to Fifth Story
Double Tee Wall Panels	0	0	0	0	0
Flat Wall Panels	1458 / 1701	2916 / 3402	4374 / 5103	5832 / 6804	7290 / 8505
Blocks	2565 / 2993	5130 / 5986	7695 / 8979	10260 / 11972	12825 / 14965
Columns to go with Blocks	5280 / 6160	10560 / 12320	15840 / 18480	21120 / 24640	26400 / 30800
Double Tee Floor Members	0	0	0	0	0
Flat Floor Slabs	0	0	0	0	0
L-Beams	720	1440	2160	2880	3600
Rectangular Beams	720	1440	2160	2880	3600
Core Wall Panels	6320 / 7373	12640 / 14745	18960 / 22118	25280 / 29490	31600 / 36863
Boxes for Service Core	100 / 100	200 / 200	300 / 300	400 / 400	500 / 500
Double Tee Roof Members	0	0	0	0	0
Flat Roof Slabs	0	0	0	0	0

TABLE XII

WIRE MESH TYPE I REQUIREMENTS
(WM 3)

Member Description	Quantities (sq ft) Consumed				
	Up to First Story	Up to Second Story	Up to Third Story	Up to Fourth Story	Up to Fifth Story
Double Tee Wall Panels	3840 / 4480	7680 / 8960	11520 / 11440	15360 / 17920	19200 / 22400
Flat Wall Panels	0	0	0	0	0
Blocks	0	0	0	0	0
Columns to go with Blocks	0	0	0	0	0
Double Tee Floor Members	0	10976	21952	32928	43904
Flat Floor Slabs	0	21952	43904	65856	87808
L-Beams	0	0	0	0	0
Rectangular Beams	0	0	0	0	0
Core Wall Panels	0	0	0	0	0
Boxes for Service Core	0	0	0	0	0
Double Tee Roof Members	10976	10976	10976	10976	10976
Flat Roof Slabs	10976	10976	10976	10976	10976

TABLE XIII

WIRE MESH TYPE II REQUIREMENTS
(WM 4)

Member Description	Quantities (ft) Consumed				
	Up to First Story	Up to Second Story	Up to Third Story	Up to Fourth Story	Up to Fifth Story
Double Tee Wall Panels	960 / 1120	1920 / 2240	2880 / 3360	3840 / 4480	4800 / 5600
Flat Wall Panels	0	0	0	0	0
Blocks	0	0	0	0	0
Columns to go with Blocks	0	0	0	0	0
Double Tee Floor Members	0	762	1524	2286	3048
Flat Floor Slabs	0	0	0	0	0
L-Beams	0	0	0	0	0
Rectangular Beams	0	0	0	0	0
Core Wall Panels	0	0	0	0	0
Boxes for Service Core	0	0	0	0	0
Double Tee Roof Members	762	762	762	762	762
Flat Roof Slabs	0	0	0	0	0

TABLE XIV

WIRE MESH TYPE III REQUIREMENTS
(WM 5)

Member Description	Quantities (sq ft) Consumed				
	Up to First Story	Up to Second Story	Up to Third Story	Up to Fourth Story	Up to Fifth Story
Double Tee Wall Panels	0	0	0	0	0
Flat Wall Panels	0	0	0	0	0
Blocks	0	0	0	0	0
Columns to go with Blocks	0	0	0	0	0
Double Tee Floor Members	0	0	0	0	0
Flat Floor Slabs	0	0	0	0	0
L-Beams	0	0	0	0	0
Rectangular Beams	0	0	0	0	0
Core Wall Panels	0	0	0	0	0
Boxes for Service Core	2448	4896	7344	9792	12240
Double Tee Roof Members	0	0	0	0	0
Flat Roof Slabs	0	0	0	0	0

TABLE XV

CONCRETE TYPE I REQUIREMENTS
(CN 6)

Member Description	Quantities (cu yd) Consumed				
	Up to First Story	Up to Second Story	Up to Third Story	Up to Fourth Story	Up to Fifth Story
Double Tee Wall Panels	0	0	0	0	0
Flat Wall Panels	0	0	0	0	0
Blocks	0	0	0	0	0
Columns to go with Blocks	0	0	0	0	0
Double Tee Floor Members	0	141	283	424	565
Flat Floor Slabs	0	272	543	815	1087
L-Beams	0	0	0	0	0
Rectangular Beams	0	0	0	0	0
Core Wall Panels	48 / 56	96 / 112	144 / 168	192 / 224	240 / 280
Boxes for Service Core	45 / 53	92 / 107	136 / 159	180 / 210	228 / 266
Double Tee Roof Members	124	124	124	124	124
Flat Roof Slabs	203	203	203	203	203

TABLE XVI

CONCRETE TYPE II REQUIREMENTS
(CN 7)

Member Description	Quantities (cu yd) Consumed				
	Up to First Story	Up to Second Story	Up to Third Story	Up to Fourth Story	Up to Fifth Story
Double Tee Wall Panels	85 / 99	169 / 197	254 / 296	338 / 395	423 / 494
Flat Wall Panels	144 / 168	288 / 336	432 / 504	576 / 672	720 / 840
Blocks	0	0	0	0	0
Columns to go with Blocks	18 / 21	36 / 42	54 / 63	72 / 84	90 / 105
Double Tee Floor Members	0	0	0	0	0
Flat Floor Slabs	0	0	0	0	0
L-Beams	24	48	72	96	120
Rectangular Beams	20	40	60	80	100
Core Wall Panels	0	0	0	0	0
Boxes for Service Core	0	0	0	0	0
Double Tee Roof Members	0	0	0	0	0
Flat Roof Slabs	0	0	0	0	0

TABLE XVII

CONCRETE TYPE III REQUIREMENTS
(CN 8)

Member Description	Quantities (Blocks) Consumed				
	Up to First Story	Up to Second Story	Up to Third Story	Up to Fourth Story	Up to Fifth Story
Double Tee Wall Panels	0	0	0	0	0
Flat Wall Panels	0	0	0	0	0
Blocks	3840 / 4480	7680 / 8960	11520 / 13440	15360 / 17920	19200 / 22400
Columns to go with Blocks	0	0	0	0	0
Double Tee Floor Members	0	0	0	0	0
Flat Floor Slabs	0	0	0	0	0
L-Beams	0	0	0	0	0
Rectangular Beams	0	0	0	0	0
Core Wall Panels	0	0	0	0	0
Boxes for Service Core	0	0	0	0	0
Double Tee Roof Members	0	0	0	0	0
Flat Roof Slabs	0	0	0	0	0

TABLE XVIII

PLANT LABOR REQUIREMENTS
(PL 9)

Member Description	Quantities (Man-hrs) Consumed				
	Up to First Story	Up to Second Story	Up to Third Story	Up to Fourth Story	Up to Fifth Story
Double Tee Wall Panels	103 / 120	206 / 240	309 / 360	412 / 480	515 / 600
Flat Wall Panels	146 / 170	292 / 340	436 / 510	584 / 680	726 / 850
Blocks	0	0	0	0	0
Columns to go with Blocks	160 / 187	320 / 374	480 / 561	640 / 748	800 / 935
Double Tee Floor Members	0	154	308	462	616
Flat Floor Slabs	0	275	550	825	1100
L-Beams	58	116	174	232	290
Rectangular Beams	44	88	132	176	220
Core Wall Panels	118 / 138	236 / 276	354 / 414	472 / 552	590 / 690
Boxes for Service Core	160 / 187	320 / 374	480 / 561	640 / 748	800 / 935
Double Tee Roof Members	165	165	165	165	165
Flat Roof Slabs	275	275	275	275	275

TABLE XIX

*ERECTION LABOR REQUIREMENTS FOR PRECAST AND PRESTRESSED MEMBERS (EL 10)

Member Description	Quantities (Man-hrs) Consumed				
	Up to First Story	Up to Second Story	Up to Third Story	Up to Fourth Story	Up to Fifth Story
Double Tee Wall Panels	250	510	780	1060	1350
Flat Wall Panels	234	478	731	993	1264
Blocks	0	0	0	0	0
Columns to go with Blocks	160	327	500	679	864
Double Tee Floor Members	0	98	200	306	416
Flat Floor Slabs	0	98	200	306	416
L-Beams	23	47	72	98	125
Rectangular Beams	21	43	66	89	114
Core Wall Panels	40	82	125	170	216
Boxes for Service Core	30	60	94	128	162
Double Tee Roof Members	98	100	102	104	106
Flat Roof Slabs	98	100	102	104	106

*Erection labor increases at the rate of two percent per increase in story height.

TABLE XX

*ERECTION LABOR REQUIREMENTS FOR BLOCK WALL
(ELB 11)

Member Description	Quantities (Man-hrs) Consumed				
	Up to First Story	Up to Second Story	Up to Third Story	Up to Fourth Story	Up to Fifth Story
Double Tee Wall Panels	0	0	0	0	0
Flat Wall Panels	0	0	0	0	0
Blocks	230 / 271	500 / 584	857 / 1001	1214 / 1418	1606 / 1876
Columns to go with Blocks	0	0	0	0	0
Double Tee Floor Members	0	0	0	0	0
Flat Floor Slabs	0	0	0	0	0
L-Beams	0	0	0	0	0
Rectangular Beams	0	0	0	0	0
Core Wall Panels	0	0	0	0	0
Boxes for Service Core	0	0	0	0	0
Double Tee Roof Members	0	0	0	0	0
Flat Roof Slabs	0	0	0	0	0

*Erection labor increases at the rate of 7.692% per increase in story height.

TABLE XXI

HIGHWAY WEIGHT LIMIT REQUIREMENTS--
FIRST LOCATION (WLR 12)

Member Description	Minimum Quantities (Truckloads) Needed				
	Up to First Story	Up to Second Story	Up to Third Story	Up to Fourth Story	Up to Fifth Story
Double Tee Wall Panels	41 / 43	84 / 86	126 / 129	168 / 172	210 / 215
Flat Wall Panels	42 / 42	84 / 84	126 / 126	168 / 168	210 / 210
Blocks	6 / 7	12 / 14	18 / 21	24 / 28	30 / 35
Columns to go with Blocks	36 / 36	72 / 72	108 / 108	144 / 144	180 / 180
Double Tee Floor Members	0	46	92	138	184
Flat Floor Slabs	0	57	114	171	228
L-Beams	9	18	27	36	45
Rectangular Beams	9	18	27	36	45
Core Wall Panels	9 / 9	18 / 18	27 / 27	36 / 36	45 / 45
Boxes for Service Core	9	18	27	36	45
Double Tee Roof Members	46	46	46	46	46
Flat Roof Slabs	57	57	57	57	57

APPENDIX C

TABLES OF QUANTITIES FOR THE COMPUTATION OF CONVERSION FACTORS AND TRUCK LOADS FOR THE SECOND AND THIRD LOCATIONS

TABLE XXII

INCREASE IN TRANSPORTATION COST UP TO THE SECOND LOCATION, ABOVE THAT OF THE FIRST LOCATION

Precast Concrete Components	First Story ($)	Second Story ($)	Third Story ($)	Fourth Story ($)	Fifth Story ($)
Double Tee Wall Panel	450 / 525	900 / 1050	1350 / 1575	1800 / 2100	2250 / 2625
Flat Wall Panel	675 / 675	1350 / 1350	2025 / 2025	2700 / 2700	3375 / 3375
Concrete Block	98.22 / 114.24	196.44 / 228.48	294.66 / 342.72	392.88 / 456.96	491.10 / 571.20
Columns to go with Block	150	300	450	600	750
Double Tee Floor Member	0	750	1500	2250	3000
Flat Floor Slab	0	1425	2850	4275	5700
Double Tee Roof Member	750	750	750	750	750
Flat Roof Slab	1425	1425	1425	1425	1425

TABLE XXIII

INCREASE IN TRANSPORTATION COST UP TO THE THIRD LOCATION, ABOVE THAT OF THE FIRST LOCATION .

Precast Concrete Components	First Story ($)	Second Story ($)	Third Story ($)	Fourth Story ($)	Fifth Story ($)
Double Tee Wall Panel	900 / 1050	1800 / 2100	2700 / 3150	3600 / 4200	4500 / 5250
Flat Wall Panel	1350 / 1350	2700 / 2700	4050 / 4050	5400 / 5400	6750 / 6750
Concrete Block	196.44 / 228.48	392.88 / 456.96	589.32 / 685.44	785.76 / 913.92	982.20 / 1142.40
Columns to go with Block	300	600	900	1200	1500
Double Tee Floor Member	0	1500	3000	4500	6000
Flat Floor Slab	0	2850	5700	8550	11400
Double Tee Roof Member	1500	1500	1500	1500	1500
Flat Roof Slab	2850	2850	2850	2850	2850

TABLE XXIV

SUMMARY OF COMPUTATION OF CONVERSION FACTORS FOR THE SECOND LOCATION

Precast Concrete Components	Total Transportation Cost First Story	Truck Loads Before Conversion for First Story	Cost Per Truck Load	Conversion Factor	Converted Truck Loads
Double Tee Wall Panel	2900 / 3050	6 / 7	483.33 / 435.71	6.36 / 5.73	39 / 41
Flat Wall Panel	3150 / 3150	9 / 9	350.00 / 350.00	4.61 / 4.61	42 / 42
Concrete Block	456 / 532	6 / 7	76.00 / 76.00	1 / 1	6 / 7
Columns to go with Block	2300	2	1150	15.13	31
Double Tee Floor Member	3450	10	345	4.54	46
Flat Floor Slab	4800	19	252.63	3.32	64
L-Beam	750	3	250	3.29	10
Rectangular Beam	750	3	250	3.29	10
Core Wall Panel	800	4	200	2.63	11
Box	800	4	200	2.63	11
Double Tee Roof Member	3450	10	345	4.54	46
Flat Roof Slab	4800	19	252.63	3.32	64

TABLE XXV

SUMMARY OF COMPUTATION OF CONVERSION FACTORS FOR THE THIRD LOCATION

Precast Concrete Components	Total Transportation Cost First Story	Truck Loads Before Conversion for First Story	Cost Per Truck Load	Conversion Factor	Converted Truck Loads
Double Tee Wall Panel	3350 / 3575	6 / 7	558.33 / 510.71	6.07 / 5.55	37 / 39
Flat Wall Panel	3825 / 3825	9 / 9	425.00 / 425.00	4.62 / 4.62	42 / 42
Concrete Block	552 / 644	6 / 7	92.00 / 92.00	1 / 1	6 / 7
Columns to go with Block	2450	2	1225	13.32	27
Double Tee Floor Member	4200	10	420	4.57	46
Flat Floor Slab	6225	19	327.63	3.56	68
L-Beam	975	3	325	3.53	11
Rectangular Beam	975	3	325	3.53	11
Core Wall Panel	1100	4	275	2.99	12
Box	1100	4	275	2.99	12
Double Tee Roof Member	4200	10	420	4.57	46
Flat Roof Slab	6225	19	327.63	3.56	68

TABLE XXVI

COMPUTATION OF CONVERTED TRUCK LOADS
FOR THE SECOND LOCATION

Precast Concrete Component	Truck Loads First Story	Truck Loads Second Story	Truck Loads Third Story	Truck Loads Fourth Story	Truck Loads Fifth Story
Double Tee Wall Panel	39 / 41	78 / 82	117 / 123	156 / 164	195 / 205
Flat Wall Panel	42 / 42	84 / 84	126 / 126	168 / 168	210 / 210
Concrete Block	6 / 7	12 / 14	18 / 21	24 / 28	30 / 35
Columns to go with Block	31	62	93	124	155
Double Tee Floor Member	0	46	92	138	184
Flat Floor Slab	0	64	128	192	256
L-Beam	10	20	30	40	50
Rectangular Beam	10	20	30	40	50
Core Wall Panel	11	22	33	44	55
Box	11	22	33	44	55
Double Tee Roof Member	46	46	46	46	46
Flat Roof Slab	64	64	64	64	64

TABLE XXVII

COMPUTATION OF CONVERTED TRUCK LOADS
FOR THE THIRD LOCATION

Precast Concrete Component	Truck Loads First Story	Truck Loads Second Story	Truck Loads Third Story	Truck Loads Fourth Story	Truck Loads Fifth Story
Double Tee Wall Panel	37 / 39	74 / 78	111 / 117	148 / 156	185 / 195
Flat Wall Panel	42 / 42	84 / 84	126 / 126	168 / 168	210 / 210
Concrete Block	6 / 7	12 / 14	18 / 21	24 / 28	30 / 35
Columns to go with Block	27	54	81	108	135
Double Tee Floor Member	0	46	92	138	184
Flat Floor Slab	0	68	136	204	272
L-Beam	11	22	33	44	55
Rectangular Beam	11	22	33	44	55
Core Wall Panel	12	24	36	48	60
Box	12	24	36	48	60
Double Tee Roof Member	46	46	46	46	46
Flat Roof Slab	68	68	68	68	68

APPENDIX D

A TYPICAL COMPUTER PROGRAM

EXPLAINED AND LISTED

The IBM Program Package MPSX360

Introduction

The IBM program package, Mathematical Programming Systems Extended 360 (MPSX360), consists of three main types of input cards, namely:

1. Job Control Language (JCL) cards.
2. Control Language Source Program cards.
3. Input Data cards.

The JCL Cards

The JCL cards constitute the first set of cards and they immediately precede the Control Language Source Program cards. An example of a set of JCL cards is as follows (66):

```
//Job name    JOB (xxxxx, xxx-xx-xxxxx), 'xxx,' etc.
// EXEC MPSX360
//MPSX1·SYSIN  DD  * .
```

The first JCL card, the JOB card, is unique for a given computer installation. Typically, the JOB card contains the Job name, the account number for the particular job, and other identifying names of the job owner. The second card tells the computer to call MPSX360 while the third card calls for the control language compiler. Other additions to the above three JCL cards are possible, depending on the requirements of the computer installation.

Control Language Source Program

The Control Language Source Program consists of a number of cards as shown in Figure 14. Each card represents a definite operation. A

```
.MPSX-PTF17.   CONTROL PROGRAM COMPILER.  MPSX  RELEASE 1  MOD LEVEL 6

0001        PROGRAM
0002        *
0003        TITLE ('SELCTN 3 MOST ECON COMBNTN 5TH STORY,1ST LOCTN')
0004        *
0005        INITIALZ
0099        MOVE (XDATA,'COMBTN')
0100        MOVE(XPBNAME,'PBFILE')
0101        CONVERT('SUMMARY')
0102        BCDOUT
0103        SETUP ('RANGE','RESOURCE','BOUND','BLDGALT')
0104        PICTURE
0105        MOVE (XOBJ,'COST')
0106        MOVE (XRHS,'COMBTN1')
0107        PRIMAL
0108        SOLUTION
0109        OPTIMIX('COST',0.,0,0,1)
0205        RANGE
0206        EXIT
0207        PEND
```

Figure 14. MPSX360 Control Language Source Program

control program must be initiated by the PROGRAM statement. The PROGRAM statement is not an executable statement and it may not have a batch (67).

The TITLE statement is an executable control program statement. The expression in parentheses in the TITLE statement constitutes the page titles to the output program. More than one TITLE statement may be used. Where up to three TITLE statements are used, the first TITLE statement will provide a heading for the first output page, while the second TITLE statement will specify the TITLE heading for the second output page. However, all subsequent output pages will bear the TITLE heading specified in the third TITLE statement.

The INITIALZ macro instruction establishes "standard" processing of all demands. Where the INITIALZ macro instruction is not used as the first statement in a control program, all the functions of the control program must be provided by the user before the execution of the first procedure (68).

An area of central memory named the Communications Region (CR) controls the operations of MPSX360. The set of instructions beginning with the verb "MOVE" specifies that the name on the right be moved into the Communications Region cell which bears the name on the left. Specifically, in the MOVE statement:

MOVE (XDATA, 'COMBTN'),

the word "COMBTN" is transferred into the Communication Region cell named "XDATA."

The CONVERT statement specifies that the input data punched on 80-column cards in Binary Coded Decimal (BCD) format be read onto the problem file (PROBFILE) (66)(67)(68). The word "SUMMARY" in parentheses after "CONVERT" makes it possible for the control program to provide statistics of both major and minor reading errors. The inclusion of "SUMMARY" is optional.

The BCDOUT statement specifies that the data in PROBFILE be converted to BCD for output, and that the data be output in the same order in which they were input.

The SETUP statement is used when some of the row constants have upper and lower limiting values (RANGE) and the decision variables are bounded (BOUND).

PICTURE creates a pictorial representation of the specified portion of the work matrix.

PRIMAL obtains an optimal feasible solution (if one exists) by solving the primal problem.

The SOLUTION instruction outputs the solution during or after optimization.

OPTIMIX appears between SOLUTION and EXIT, and controls the sequencing of the branch-and-bound iterations after an optimum solution to the unrestricted LP problem (that is an LP problem which satisfies all constraints and bounds, except the integer requirement).

If it is desired to establish the effect on the optimal solution, of varying the RHS constants and the objective function coefficients (sensitivity analysis), the RANGE statement is used.

The last two cards, EXIT and PEND, mark the end of the control program. Since the JCL program treats the whole of the control program as input data, the JCL card "/*" follows the PEND card.

A typical input data format is listed in Figure 15. The first data card contains the two words "NAME" and "COMBTN," and gives the

```
.MPSX-PTF17.   SELCTN 3 MOST ECON COMBNTN 5TH STORY.1ST LOCTN.MPSX-PTF17.   SELCTN 3 MOST ECON COMBNTN 5TH STORY.1ST LOCTN

NAME          COMBTN
ROWS
 N  COST
 G  PS1
 G  RB2
 G  WM3
 L  WM4
 L  WM5
 G  CN6
 G  CN7
 L  CN8
 G  PL9
 G  EL10
 L  EL811
 G  WLR12
 G  CR13
COLUMNS
    INTORG    'MARKER'                 'INTORG'
    X0151     COST       257935.0000   PS1        73216.01000
    X0151     RB2         35200.00200  WM3        74030.00300
    X0151     WM4          8610.04000  CN6          929.00600
    X0151     CN7           543.07000  PL9         2176.08000
    X0151     EL10         2213.01100  WLR12        525.01200
    X0151     CR13            1.00000
    X0251     COST       256441.0000   PS1        73216.01200
    X0251     RB2          4100.01200  WM3        74080.01300
    X0251     WM4          8610.01400  WM5        12240.01500
    X0251     CN6           917.01600  CN7          543.01700
    X0251     PL9          2386.01900  EL10        2159.01100
    X0251     WLR12         510.00000  CR13           1.00000
    X0351     COST       267535.0000   PS1        77216.00000
    X0351     RB2         40463.00200  WM3        66304.00500
    X0351     WM4          9410.00400  CN6          969.00600
    X0351     CN7           594.00700  PL9         2291.00900
    X0351     EL10         2202.00110  WLR12        535.01210
    X0351     CR13            1.00000
    X0451     COST       268324.0000   PS1        77216.00100
    X0451     RB2          4100.01040  WM3        66304.00500
    X0451     WM4          9410.00600  WM5        12240.00700
    X0451     CN6           955.00860  CN7          594.00690
    X0451     PL9          2536.00760  EL10        2148.01900
    X0451     WLR12         520.00120  CR13           1.00000
    X0551     COST       273738.0000   PS1       106144.0000
    X0551     RB2         35200.00570  WM3       117984.0000
    X0551     WM4          5562.00160  CN6         1451.00900
    X0551     CN7           543.01610  PL9         2660.01720
    X0551     EL10         2213.01150  WLR12        569.06750
    X0551     CR13            1.00000
    X0651     COST       272244.0000   PS1       106144.0100
    X0651     RB2          4100.00180  WM3       117984.0100
    X0651     WM4          5562.00000  WM5        12240.00500
    X0651     CN6          1439.00000  CN7          543.01500
    X0651     PL9          2870.06900  EL10        2159.09600
    X0651     WLR12         554.00140  CR13           1.00000
    X0751     COST       283341.0000   PS1       110144.0000
    X0751     RB2         40463.01500  WM3       110206.0100
    X0751     WM4          6362.00900  CN6         1491.01750
    X0751     CN7           594.00170  PL9         2775.00140
    X0751     EL10         2202.00101  WLR12        579.00120
    X0751     CR13            1.00000
    X0851     COST       284627.0000   PS1       110144.0100
    X0851     RB2          4100.00181  WM3       110208.0000
    X0851     WM4          6362.00720  WM5        12240.00000
    X0851     CN6          1477.00191  CN7          594.01960
    X0851     PL9          3020.01610  EL10        2148.01100
    X0851     WLR12         564.00000  CR13           1.00000
    X0951     COST       270709.0000   PS1        66656.00190
    X0951     RB2         42490.01500  WM3        54880.00500
    X0951     WM4          3610.00950  CN6          929.01517
    X0951     CN7           840.00690  PL9         2387.00450
    X0951     EL10         2127.03690  WLR12        530.00910
    X0951     CR13            1.00000
    X1051     COST       264215.0000   PS1        66656.01000
    X1051     RB2          8390.01560  WM3        54880.01700
    X1051     WM4          3810.04500  WM5        12240.01000
    X1051     CN6           917.01910  CN7          840.01760
    X1051     PL9          2597.01690  EL10        2073.00120
    X1051     WLR12         515.00000  CR13           1.00000
    X1151     COST       281450.0000   PS1        71896.00000
    X1151     RB2         48968.00000  WM3        43904.00000
    X1151     WM4          3610.00000  CN6          926.00000
    X1151     CN7           940.01910  PL9         2541.00900
    X1151     EL10         2116.00100  WLR12        530.00600
    X1151     CR13            1.00000
    X1251     COST       282736.0000   PS1        71396.04500
    X1251     RB2         12605.00000  WM3        43904.00000
    X1251     WM4          3810.01600  WM5        12240.07600
    X1251     CN6           955.01600  CN7          940.00000
    X1251     PL9          2786.00100  EL10        2062.01650
    X1251     WLR12         515.08000  CR13           1.00000
    X1351     COST       286512.0000   PS1       101584.0000
    X1351     RB2         42490.05100  WM3        98784.06500
    X1351     WM4           762.01400  CN6         1451.00900
    X1351     CN7           840.01710  PL9         2871.00690
    X1351     EL10         2127.00000  WLR12        559.00560
    X1351     CR13            1.00000
    X1451     COST       285018.0000   PS1       101584.0000
    X1451     RB2          8390.01450  WM3        98784.09100
    X1451     WM4           762.00410  WM5        12240.00100
    X1451     CN6          1439.00614  CN7          840.00614
    X1451     PL9          3081.01060  EL10        2073.06940
    X1451     WLR12         559.05400  CR13           1.00000
    X1551     COST       297253.0000   PS1       104824.0100
    X1551     RB2         48968.00160  WM3        87684.0100
    X1551     WM4           762.01560  CN6         1491.00170
    X1551     CN7           940.01061  PL9         3025.00650
    X1551     EL10         2116.01760  WLR12        574.06171
    X1551     CR13            1.00000
```

Figure 15. A Typical MPSX360 Input Data Format

MPSX-PTF17. SELCTN 3 MOST ECON COMBNTN 5TH STORY.1ST LOCTN

X1651	COST	298539.0000	PS1	104824.0000
X1651	RB2	12605.00000	WM3	67608.00100
X1651	WM4	762.01016	WM5	12240.01600
X1651	CN6	1477.00100	CN7	540.06810
X1651	PL9	30270.01900	EL10	2062.01760
X1651	WLR12	559.00000	CR13	1.00000
X1751	COST	291374.0000	PS1	56816.00600
X1751	RB2	74425.00160	WM3	54080.00700
X1751	WM4	3610.00560	CN6	529.00760
X1751	CN7	876.00171	CN8	19200.00800
X1751	PL9	2461.00760	EL10	1727.00110
X1751	ELB11	1606.00450	WLR12	530.00760
X1751	CR13	1.00000		
X1851	COST	289880.0000	PS1	56816.00100
X1851	RB2	43325.00810	WM3	54080.00800
X1851	WM4	3610.00960	WM5	12240.00700
X1851	CN6	917.00680	CN7	876.00515
X1851	CN8	19200.00180	PL9	2671.00710
X1851	EL10	1673.00510	ELB11	1606.00450
X1851	WLR12	515.00560	CR13	1.00000
X1951	COST	295539.0000	PS1	60416.00700
X1951	RB2	86228.00560	WM3	43904.04800
X1951	WM4	3810.01940	CN6	569.01560
X1951	CN7	963.01890	CN8	22400.00100
X1951	PL9	2626.00450	EL10	1716.01560
X1951	ELB11	1876.05160	WLR12	535.01760
X1951	CR13	1.00000		
X2051	COST	296825.0000	PS1	60416.05100
X2051	RB2	49865.05600	WM3	43904.00000
X2051	WM4	3810.00121	WM5	12240.02000
X2051	CN6	955.00216	CN7	983.00768
X2051	CN8	22400.00510	PL9	2971.00760
X2051	EL10	1662.01910	ELB11	1876.05160
X2051	WLR12	520.02012	CR13	1.00000
X2151	COST	307177.0000	PS1	91744.02100
X2151	RB2	74425.02600	WM3	98784.01600
X2151	WM4	2514.07610	CN6	1451.04150
X2151	CN7	876.00217	CN8	19200.00200
X2151	PL9	2945.00120	EL10	1726.00000
X2151	ELB11	1606.05160	WLR12	574.01760
X2151	CR13	1.00000		
X2251	COST	305683.0000	PS1	91744.01700
X2251	RB2	4325.06150	WM3	98784.00900
X2251	WM4	2514.00769	WM5	12240.06200
X2251	CN6	1439.05160	CN7	876.02170
X2251	CN8	19200.01218	PL9	2155.09180
X2251	EL10	1673.09190	ELB11	1606.01910
X2251	WLR12	559.00760	CR13	1.00000
X2351	COST	311342.0000	PS1	93344.00600
X2351	RB2	86225.01760	WM3	87608.04100
X2351	WM4	3314.01900	CN6	1491.00910
X2351	CN7	963.01470	CN8	22400.00000
X2351	PL9	3110.00290	EL10	1716.00210
X2351	ELB11	1876.01101	WLR12	579.00120

MPSX-PTF17. SELCTN 3 MOST ECON COMBNTN 5TH STORY.1ST LOCTN

X2351	CR13	1.00000		
X2451	COST	312628.0000	PS1	93344.00200
X2451	RB2	49865.00760	WM3	87608.04500
X2451	WM4	3314.01650	WM5	12240.00900
X2451	CN6	1477.04600	CN7	583.00690
X2451	CN8	22400.01600	PL9	3355.09160
X2451	EL10	1662.00760	ELB11	1876.04500
X2451	WLR12	564.01020	CR13	1.00000
X2551	COST	800000.0000	PS1	81448.00600
X2551	RB2	35200.02500	WM3	74080.04700
X2551	WM4	7848.00254	CN6	929.00261
X2551	CN7	543.07150	PL9	2286.07150
X2551	EL10	2213.09160	WLR12	536.07150
X2551	CR13	1.00000		
X2651	COST	259038.0000	PS1	81448.01700
X2651	RB2	4100.00415	WM3	74080.02400
X2651	WM4	7848.02640	WM5	12240.01500
X2651	CN6	917.01670	CN7	543.01614
X2651	PL9	2496.07610	EL10	2159.04600
X2651	WLR12	521.00560	CR13	1.00000
X2751	COST	270135.0000	PS1	65448.00100
X2751	RB2	40463.02600	WM3	66304.01700
X2751	WM4	8648.01750	CN6	569.07510
X2751	CN7	594.01450	PL9	2401.07600
X2751	EL10	2202.09500	WLR12	546.00127
X2751	CR13	1.00000		
X2851	COST	271421.0000	PS1	85448.00600
X2851	RB2	4100.00284	WM3	66304.00300
X2851	WM4	8648.01760	WM5	12240.00900
X2851	CN6	955.07610	CN7	594.01510
X2851	PL9	2646.01900	EL10	2143.99950
X2851	WLR12	531.00000	CR13	1.00000
X2951	COST	276335.0000	PS1	114376.0100
X2951	RB2	3520.00760	WM3	117934.0000
X2951	WM4	4600.02910	CN6	1451.06150
X2951	CN7	543.07290	PL9	2770.05410
X2951	EL10	2213.02910	WLR12	580.01200
X2951	CR13	1.00000		
X3051	COST	274841.0000	PS1	114376.0000
X3051	RB2	4100.00000	WM3	117954.0000
X3051	WM4	4800.00000	WM5	12240.00000
X3051	CN6	1439.00000	CN7	543.00000
X3051	PL9	2980.00000	EL10	2159.00000
X3051	WLR12	565.01250	CR13	1.00000
X3151	COST	285938.0000	PS1	11376.00000
X3151	RB2	40463.00000	WM3	110208.0000
X3151	WM4	5600.01040	CN6	1491.00000
X3151	CN7	594.00000	PL9	2885.00000
X3151	EL10	2202.00000	WLR12	590.00000
X3151	CR13	1.00000		
X3251	COST	287227.0000	PS1	118376.0100
X3251	RB2	4100.00320	WM3	110208.0100
X3251	WM4	5600.00000	WM5	12240.00000
X3251	CN6	1477.01000	CN7	594.00160

Figure 15. (Continued)

.MPSX-PTF17. SELCTN 3 MOST ECON COMBNTN 5TH STORY.1ST LOCTN

X3251	PL9	3130.00450	EL10	2148.01800
X3251	WLR12	575.00000	CR13	1.00000
X3351	COST	273306.0000	PS1	76889.00000
X3351	RB2	42490.01000	WM3	54880.05000
X3351	WM4	3046.00700	CN6	929.07500
X3351	CN7	640.00175	PL9	2497.07100
X3351	EL10	2127.00115	WLR12	541.00620
X3351	CR13	1.00000		
X3451	COST	271612.0000	PS1	76888.01400
X3451	RB2	8390.01780	WM3	54880.03400
X3451	WM4	3048.00345	WM5	12240.00300
X3451	CN6	917.00316	CN7	840.00570
X3451	PL9	2707.00000	EL10	2073.00140
X3451	WLR12	526.00120	CR13	1.00000
X3551	COST	284047.0000	PS1	80126.00900
X3551	RB2	48968.01500	WM3	43904.01400
X3551	WM4	3048.01060	CN6	967.01756
X3551	CN7	940.00156	PL9	2651.00190
X3551	EL10	2116.00101	WLR12	541.00170
X3551	CR13	1.00000		
X3651	COST	285333.0000	PS1	80128.00100
X3651	RB2	12605.00150	WM3	43904.00100
X3651	WM4	3048.00364	WM5	12240.00200
X3651	CN6	955.00316	CN7	940.00756
X3651	PL9	2896.00590	EL10	2062.00500
X3651	WLR12	526.00180	CR13	1.00000
X3751	COST	289109.0000	PS1	109816.0000
X3751	RB2	42490.04000	WM3	98784.00300
X3751	CN6	1451.00100	CN7	840.00000
X3751	PL9	2981.00000	EL10	2127.00160
X3751	WLR12	585.00161	CR13	1.00000
X3851	COST	287615.0000	PS1	109816.0000
X3851	RB2	8390.00120	WM3	98784.00600
X3851	WM5	12240.00100	CN6	1439.00750
X3851	CN7	840.00156	PL9	3191.00190
X3851	EL10	2073.00840	WLR12	570.00123
X3851	CR13	1.00000		
X3951	COST	299850.0000	PS1	113056.0000
X3951	RB2	48968.00140	WM3	87808.00500
X3951	CN6	1491.00510	CN7	940.00739
X3951	PL9	3135.00600	EL10	2116.00000
X3951	WLR12	585.00391	CR13	1.00000
X4051	COST	301136.0000	PS1	113056.0100
X4051	RB2	12605.00590	WM3	87808.01500
X4051	WM5	12240.01400	CN6	1477.00145
X4051	CN7	940.00160	PL9	3380.00164
X4051	EL10	2062.00120	WLR12	570.00180
X4051	CR13	1.00000		
X4151	COST	293971.0000	PS1	67048.00100
X4151	RB2	74425.01600	WM3	54880.00700
X4151	WM4	3048.00190	CN6	929.00134
X4151	CN7	876.00000	CN8	19200.00000 RHS
X4151	PL9	2571.00860	EL10	1727.01560
X4151	ELB11	1606.00113	WLR12	541.00111

.MPSX-PTF17. SELCTN 3 MOST ECON COMBNTN 5TH STORY.1ST LOCTN

X4151	CR13	1.00000		
X4251	COST	292477.0000	PS1	67048.00100
X4251	RB2	43325.06180	WM3	54880.00400
X4251	WM4	3048.00460	WM5	12240.00100
X4251	CN6	917.00165	CN7	876.00960
X4251	CN8	19200.00460	PL9	2781.00560
X4251	EL10	1763.00102	ELB11	1606.01150
X4251	WLR12	526.00161	CR13	1.00000
X4351	COST	298136.0000	PS1	68648.00000
X4351	RB2	86228.00000	WM3	43904.00000
X4351	WM4	3048.00190	CN6	969.00150
X4351	CN7	983.00360	CN8	22400.00500
X4351	PL9	2736.00195	EL10	1716.00360
X4351	ELB11	1876.00150	WLR12	546.00530
X4351	CR13	1.00000		
X4451	COST	299422.0000	PS1	68648.00900
X4451	RB2	49865.00600	WM3	43904.00500
X4451	WM4	3048.00800	WM5	12240.00700
X4451	CN6	955.00446	CN7	983.00437
X4451	CN8	22400.00610	PL9	2981.00910
X4451	EL10	1662.00110	ELB11	1376.00120
X4451	WLR12	531.00157	CR13	1.00000
X4551	COST	309774.0000	PS1	99976.00600
X4551	RB2	74425.00000	WM3	98784.00100
X4551	WM4	1757.00000	CN6	1451.00000
X4551	CN7	676.00700	CN8	19200.00100
X4551	PL9	3055.00180	EL10	1727.00450
X4551	ELB11	1606.00360	WLR12	535.00412
X4551	CR13	1.00000		
X4651	COST	308280.0000	PS1	99976.00800
X4651	RB2	43325.01400	WM3	98784.00500
X4651	WM4	1752.00450	WM5	12240.00600
X4651	CN6	1439.00160	CN7	876.00760
X4651	CN8	19200.00460	PL9	2265.00550
X4651	EL10	1673.00116	ELB11	1606.00000
X4651	WLR12	570.00000	CR13	1.00000
X4751	COST	313939.0000	PS1	101576.0000
X4751	RB2	86225.00000	WM3	87808.00700
X4751	WM4	2552.00400	CN6	491.00000
X4751	CN7	983.00000	CN8	22400.00100
X4751	PL9	3220.00300	EL10	1716.00430
X4751	ELB11	1876.00120	WLR12	590.00000
X4751	CR13	1.00000		
X4851	COST	315223.0000	PS1	101576.0000
X4851	RB2	49065.00000	WM3	87808.00000
X4851	WM4	2552.00640	WM5	12240.00000
X4851	CN6	1477.00510	CN7	933.01420
X4851	CN8	22400.01230	PL9	3465.00150
X4851	EL10	1662.00246	ELB11	1876.00450
X4851	WLR12	575.00000	CR13	1.00000
INTEND	'MARKER'		'INTEND'	
COMBTN1	PS1	165000.0000	RB2	10998.00000
COMBTN1	WM3	126000.0000	WM4	28998.00000

Figure 15. (Continued)

```
.MPSX-PTF17.   SELCTN 3 MOST ECON COMBNTN 5TH STORY,1ST LOCTN

    COMBTN1   WM5        34998.00000   CN6       2700.00000
    COMBTN1   CN7         1620.00000   CN8      69000.00000
    COMBTN1   PL9         6300.00000   EL10      4800.00000
    COMBTN1   EL811       5700.00000   WLR12     1245.00000
    COMBTN1   CR13           3.00000
RANGES
    RESOURCE  PS1       190000.0000    RD2     152000.0000
    RESOURCE  WM3       231000.0000    CN6       1900.00000
    RESOURCE  CN7         1930.00000   PL9       4200.00000
BOUNDS
 UP BLDGALT   X0151          1.00000
 UP BLDGALT   X0251          1.00000
 UP BLDGALT   X0351          1.00000
 UP BLDGALT   X0451          1.00000
 UP BLDGALT   X0551          1.00000
 UP BLDGALT   X0651          1.00000
 UP BLDGALT   X0751          1.00000
 UP BLDGALT   X0851          1.00000
 UP BLDGALT   X0951          1.00000
 UP BLDGALT   X1051          1.00000
 UP BLDGALT   X1151          1.00000
 UP BLDGALT   X1251          1.00000
 UP BLDGALT   X1351          1.00000
 UP BLDGALT   X1451          1.00000
 UP BLDGALT   X1551          1.00000
 UP BLDGALT   X1651          1.00000
 UP BLDGALT   X1751          1.00000
 UP BLDGALT   X1851          1.00000
 UP BLDGALT   X1951          1.00000
 UP BLDGALT   X2051          1.00000
 UP BLDGALT   X2151          1.00000
 UP BLDGALT   X2251          1.00000
 UP BLDGALT   X2351          1.00000
 UP BLDGALT   X2451          1.00000
 UP BLDGALT   X2551          1.00000
 UP BLDGALT   X2651          1.00000
 UP BLDGALT   X2751          1.00000
 UP BLDGALT   X2851          1.00000
 UP BLDGALT   X2951          1.00000
 UP BLDGALT   X3051          1.00000
 UP BLDGALT   X3151          1.00000
 UP BLDGALT   X3251          1.00000
 UP BLDGALT   X3351          1.00000
 UP BLDGALT   X3451          1.00000
 UP BLDGALT   X3551          1.00000
 UP BLDGALT   X3651          1.00000
 UP BLDGALT   X3751          1.00000
 UP BLDGALT   X3851          1.00000
 UP BLDGALT   X3951          1.00000
 UP BLDGALT   X4051          1.00000
 UP BLDGALT   X4151          1.00000
 UP BLDGALT   X4251          1.00000
 UP BLDGALT   X4351          1.00000
 UP BLDGALT   X4451          1.00000
```

```
.MPSX-PTF17.   SELCTN 3 MOST ECON COMBNTN 5TH STORY,1ST LOCTN

 UP BLDGALT   X4551          1.00000
 UP BLDGALT   X4651          1.00000
 UP BLDGALT   X4751          1.00000
 UP BLDGALT   X4851          1.00000
ENDATA
```

Figure 15. (Continued)

NAME of the data set. "COMBTN" must be the same as that used in the control program statement: MOVE (XDATA, 'COMBTN'). The JCL statement: //MPSX2·SYSIN DD * precedes the data set.

The indicator card "ROWS" is followed by the data cards which state the names of the rows and the types of constraints they are.

N means no constraint.

G means greater than or equal to ($\geq$).

L means less than or equal to ($\leq$).

If a constraint row is an equality then E is used in place of N, G, or L.

The indicator card "COLUMNS" introduces the data cards containing the coefficients of the decision variables. The words "INTORG," "MARKER," and "INTORG" precede the list of decision variables which are integer. Similarly, "INTEND," "MARKER," and "INTEND" terminate such a list. The coefficients of the decision variables are listed column by column. However, the sequence of listing the columns does not matter. Thus all the coefficients of the decision variable X0651 can be listed before those of X0151, but the sequence of the row names, e.g.,

COST

RB2

may not be altered in either X0651 or X0151.

RHS, RANGES, and BOUNDS are indicator cards. All RHS constants are given a group name COMBTN1. The group names for all RHS constants which have RANGES, and all decision variables having upper and lower BOUNDS are RESOURCE and BLDGALT, respectively. If UP is punched in the second and third columns of a data card in the BOUNDS section, it means that the numerical quantity on that card is the upper bound value of the decision variable on that card. LO may be punched on a second card for the same decision variable and in the same columns as UP, if the decision variable has a lower bound value. Since all decision variables in Figure 15 are positive, their lower bound values are zero and do not have to be specified under the BOUNDS section.

The card, ENDATA, indicates the end of the data set.

In all the data cards under the sections

COLUMNS

RHS

RANGES

BOUNDS

the following field specifications must be met:

Columns 5-12	Alphanumeric
Columns 15-22	Alphanumeric
Columns 25-36	Numeric
Columns 40-47	Alphanumeric
Columns 50-61	Numeric.

Under the BOUNDS section, two exceptions are made. First, columns 2-3 contain either of the two-letter indicators "UP" or "LO" to show whether it is the upper or lower bound value of the decision variable that is punched on the particular card. Second, columns 25-61 are not used.

VITA

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