University of Alberta

LINEAR OPTIMIZATION APPLICATIONS IN CONSTRUCTION

by

HECTOR HERNANDO GUTIERREZ ©

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ABSTRACT

Construction engineering and management problems present many opportunities for the application of operations research (O.R). Although a number of applications have been documented in the literature, their use in industry has been scarce. This thesis attempts to bridge the gap between the construction practitioner and O.R. tools through the use of new computing technologies.

This thesis provides a framework that can be utilized in modeling construction problems using linear programming with the assistance of computer methods. This is achieved through the use of new computing technologies (e.g. event driven and object oriented programming) and by experimenting with the modeling and programming of two problems: concrete mix design and equipment allocation. In the first application the objective is to minimize the total cost of concrete subject to specified product requirements, in the second application the objective is to minimize project duration through optimization of allocated equipment.

The solution process of these two problems and its automation are discussed in light of linear programming models. The research resulted in the development of two computer programs which are used to solve these problems. Their characteristics, limitations and main features are discussed.

CHAPTER 1: INTRODUCTION

BACKGROUND

Many construction management proolems can be solved using operation research as demonstrated by many researchers (see Starks and Meyer, 1983, for example). Linear programming (LP) and its derivates (e.g. mixed integer programming, transportation and assignment problems) are particularly noticeable in the construction management literature. The popularity of LP applications can be attributed to a number of reasons including the fact that LP is more amenable to manual solutions (i.e. simplex method) compared to other operations research (O.R.) methods, the nature of problems encountered in construction as demonstrated in Starks and Meyer, 1983, and others.

The recent surge in computer use has also contributed to more applications of analytical, scientific and OR methods in solving construction management problems. Network techniques such as the critical path method (CPM) and Program Evaluation and Review Technique (PERT) have become common in construction contractors'offices, for example. Other more involved OR techniques such as LP exist mainly in academia or as a black box computer program. The main reason for the reluctance of construction practitioners in adopting such powerful techniques include the following:

1) Complexity involved in creating an OR model for a given problem. Construction project managers are not necessarily college graduates which makes it difficult to comprehend the required theories.

2) Effort required for preparing and maintaining an OR model. A typical Construction problem such as optimization of cut and fill on a highway construction project may

involve over fifty variables and one hundred constraints. This obviously takes considerable effort to put in the format required by most general purpose OR computer tools such as LINDO.

3) Dynamic nature of construction problems. Most problems faced by construction engineers and managers are dynamic in nature. Dynamic in this context means that the problem conditions may change with time thus necessitating modifying the OR model and revising a program solution.

4) Time and resources available for planning of construction works. In most cases, construction contractors do not spend considerable amount of resources planning their work up front. This is specially true for small to mid-size contractors.

The objective of this research is to facilitate the use of more OR methods in solving construction related problems by overcoming the stated obstacles. In particular, the thesis provides a framework that can be utilized in modeling construction problems using LP with the assistance of computer methods. This will be achieved through 1) Use of new computing technologies such as event driven and object oriented programming.
2) Experimenting with the modeling and programming of a concrete mix design application and an equipment application. 3) Implementation of the solutions on computer software for use by construction companies.

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CHAPTER 2: CONCEPTUAL MODEL

INTRODUCTION

The objective of this research is to provide the construction practitioner with easy access to powerful OR tools. To accomplish this, a computer program will be designed as a shell that will capture the required input of the problem from the user, construct the required LP and provide the optimum solution.

Generalizing a LP model for all types of construction problems is not possible. It is however, conceivable that for a given problem, the same solution steps can be followed for automating the process thus minimizing the effort required in preparing similar tools.

This paper will describe the state of the art in LP applications in construction and review the essential ingredients of the computerization process. This approach will be followed in automating the process of building the LP for concrete mix design in Chapter 3 and LP for the equipment allocation problem in Chapter 4.

REVIEW OF OPERATIONS RESEARCH APPLICATIONS IN THE CONSTRUCTION INDUSTRY

A large number of mathematical models have been developed for construction. Arshenas and Haber (1990), proposed a model for the economic optimization of construction project scheduling. A mixed integer programming model in which the objective was to minimize the sum of the costs of all resources used in a project was presented. The model can handle linear as well as non-linear cost functions.

Karaa and Anas (1986), presented a mixed integer programming model for the management of resources throughout the project life. Based on CPM analysis, the model minimizes the total cost of leased resources.

Stark and Mayer (1981) suggested a linear programming model whose objective was to determine the most economical solution for the selection of borrow and disposal sites, equipment and material distribution for earthmoving projects. Easa (1987) presented a similar model but he considered non-constant unit costs. Jayawardane and Harris (1990) also worked on a similar model but they additionally considered the project duration to find the best solution for an earthmoving project.

Kanperkiewicz (1994) applied linear programming to the problem of optimum cost of concrete mix components. The optimization model was based on three main constraints, namely:

1) strength constraint - which describes the relationship between 28-d strength and the cement/ water ratio;

2) water requirement constraint - which describes the relationship between water content for specific quantities of cement and total aggregates; and

3) absolute volume constraint - which describes the condition that the total volume of the components of concrete should correspond to the value of 1 m^3.

Rashwan, et al. (1989) developed a non-linear programming model to determine the optimum percentage of fly ash in masonry concrete block mixes that minimizes the cost of the mix while maintaining the required properties of the block. The optimization process was iterative with each complete cycle containing both experimental and analytical phases. The experimental phase was performed first, during which a set of historical data was produced and provided as input to the analytical phase. During the analytical phase, simulated functions representing the relationships among different variables were developed using the results of the experimental phase. The developed relationships were then solved using a non-linear programming technique. The results of the mathematical optimization process (the analytical phase) served as input to the subsequent experimental phase for the following cycle. Cycles were then repeated until convergence occurred between both the experimental and analytical results.

In general three areas have been investigated in light of mathematical models: project scheduling, equipment management and construction materials (e.g. concrete mixes).

Keeping in mind the main objectives of this research it was decided to analyze two specific problems using linear programming concepts:

1. Design of concrete mixes

2. Construction equipment allocation

Concrete mix design

The main concern in concrete manufacturing (ready-mix concrete plants) is to find the right amount of each ingredient, and predict concrete properties (e.g. strength, slump, air content) under certain conditions (e.g. moisture, gradation) at lowest possible cost. The goal is to optimize concrete mix production and overall concrete mix performance.

When historical information of a concrete plant is reviewed it can be found that for mixes with similar specifications there are variations in the amount of the ingredients and in the quality control parameters (strength, slump and air content). This suggests that there has to be an "optimum" mix, which in this case would be the one that meets the requirements at the lowest possible cost. In other words, it is possible to get an optimum mix design for specific conditions (materials properties, material sources etc.) based on previous design information which obviously include amounts and properties of the ingredients as well as performance parameters such as strength, slump and air content.

Equipment allocation

Medium and large construction companies involved in equipment intensive work are required to develop a plan or strategy regarding rental and allocation of equipment to various projects. Equipment should be allocated according to certain requirements such as the project schedules and priorities. Many times the equipment owned by the company will not be enough to handle the amount of work to be done. In such a case the company rents equipment to support its fleets.

The right equipment management policy will contribute to making the company more profitable and efficient. In general terms, equipment management should be based on the needs and the objectives of the company such as to maximize profit, minimize cost and decrease idle time of the equipment.

COMPUTER IMPLEMENTATION

The computer implementation follows the following steps:

- Design and development of user interfaces.
- Automated generation of linear programming models for the two specific problems: concrete mix design and equipment allocation
- Solution of the linear programming for optimum results.
- Reporting the solution in a form suitable for the problem domain.

In developing computer implementations the following issues should be considered:

1) Flexibility of the modeling process.

2) Maintainability of the solution process.

In addressing these issues the intent is to make use of commercially available computer programs for solving the LP and for scheduling. This will allow us to focus on the computer shell, the object of which is to capture the LP input from the user in a manner familiar with his domain. The main challenge in this process is automating the process of generating the LP, solving for optimum results and presenting them in a simple manner.

Based on all this, a computer implementation process was developed. The concept is depicted in Figure 2-1. The components of the system are defined by the requirements mentioned before. These components are:

- A linear programming software
- A database and
- A shell

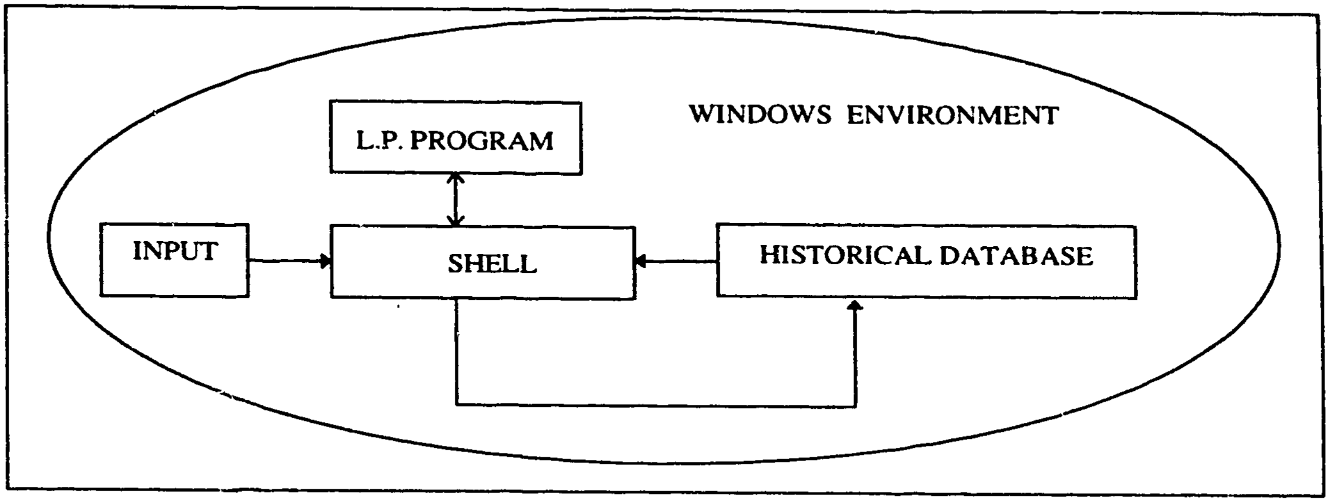

FIGURE 2-1 INTEGRATED PLATFORM

The shell is developed for a windows environment. The main part of the model is the shell system. Its main function is to integrate the other elements.

Once the input has been received the system will automatically develop the model. Once the model has been generated it will be transferred to LINDO for solving. The answers provided by LINDO are automatically retrieved and utilized in making decisions.

When storage or updating of information is required the shell will form the link between the database and the mathematical model.

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CHAPTER 3: CONCRETE MIX DESIGN OPTIMIZATION

INTRODUCTION

Concrete is one of the most popular materials used in the construction industry. This popularity and also the highly competitive environment in today's market created the necessity for developing new methodologies and technologies to produce concrete with better quality at the minimum cost.

The objective of this work is to develop a computerized program for a linear programming formulation of the concrete mix design problem. The implementation should have the following attributes:

- Integration and self containment in such a way that the user does not have to use more than one system to solve a mix design problem.
- Flexible to allow implementation for different organizations.

To achieve this objective the following was done:

1. A linear programming formulation proposed by Rashwan was studied and adopted.
2. A set of mix designs from Lafarge Construction Materials was selected for a prototype development.
3. A database was created to facilitate the manipulation of the mix information.
4. A program was developed in Visual Basic.
5. A case study was used to validate the linear programming model.

LINEAR OPTIMIZATION MODEL FOR CONCRETE MIX DESIGN

Rashwan (1996) developed a model for the optimum productivity/performance of ready-mix concrete. The model consists of a large number of functions that describe the relationships among the many variables affecting the design, batching, mixing, delivery and quality control of ready-mix concrete. These functions were constructed using historical data.

For each relationship between a set of variables (e.g., water/cement ratio versus 28-days strength) two boundary functions can be developed, one describes the upper limit, and the second describes the lower limit. These two boundaries, linearly expressed, contain all the other points, as recorded from historical data.

Some of these relationships are expressed as the multiplication or division of variables. This fact would convert the model from a linear programming one into a non linear programming model. In order to avoid this, discrete values for these variables are selected from a range of the available historical data. Such discrete values can be embedded within the feasible region created by the continuous variable functions, and then linked to such continuous variables through zero-one parameters. The model provides optimum amounts of concrete ingredients and its cost, predicted 28-days strength, air content, slump, and concrete temperature.

The problem is basically a matter of improving the concrete manufacturing process rather than solving it. The following sections describe the objective function and the constraints used by the model.

VARIABLES OF THE MODEL

Variables are defined as all factors that may affect or be affected in the process of concrete production. For example, cement quantity is a factor that affects others, such as 28-days compressive strength. Concrete temperature, on the other hand, is a factor that is affected by, among other factors, the cement content and type. Tables 3-1 and 3-2 show the variables identified.

INGREDIENT OR QUALITY CONTROL PARAMETER	VARIABLE
CEMENT	AMOUNT TYPE SOURCE
COARSE AGGREGATE	AMOUNT TYPE SOURCE GRADATION MOISTURE CONDITION
FINE AGGREGATE	AMOUNT TYPE SOURCE GRADATION MOISTURE CONDITION FINESS MODULE
FLY ASH	AMOUNT SOURCE
WATER	AMOUNT
ADMIXTURE	TYPE AMOUNT SOURCE
SLUMP	IN PLANT ON SITE
AIR CONTENT	IN PLANT ON SITE
UNIT WEIGHT	IN PLANT ON SITE
CONCRETE TEMPERATURE	IN PLANT ON SITE
TRANSPORTATION TIME	ELAPSED TIME

TABLE 3-1 VARIABLES CONSIDERED IN THE CONCRETE MANUFACTURING PROCESS

Based on these variables different relationships can be considered. Table 3-2 depicts the relationships used by the model.

RELATION	INDEPENDENT VARIABLE	DEPENDENT VARIABLE
1	% FINES OF TOTAL AGGREGATES	SLUMP ON SITE(mm)
2	% FINES OF TOTAL AGGREGATES	AIR CONTENT(%)
3	% FINES OF TOTAL AGGREGATES	28-D COMPRESSIVE STRENGTH (Mpa)
4	CEMENT CONTENT (Kg)	28-D COMPRESSIVE STRENGTH (Mpa)
5	CEMENT + FLY ASH (Kg)	28-D COMPRESSIVE STRENGTH (Mpa)
6	WATER / (CEMENT+ FLYASH)	SLUMP (mm)
7	WATER / (CEMENT+ FLYASH)	28-D COMPRESSIVE STRENGTH (Mpa)
8	CONCRETE TEMPERATURE	AIR CONTENT(%)
9	AIR CONTENT(%)	28-D COMPRESSIVE STRENGTH (Mpa)
10	TOTAL ELAPSED TIME (min)	SLUMP ON SITE(mm)
11	% FINES OF TOTAL AGGREGATES	CEMENT + FLY ASH (Kg)
12	CONCRETE TEMPERATURE (°C)	TOTAL WATER REQUIREMENT(Kg)
13	AGE (DAYS)	COMPRESSIVE STRENGTH (Mpa)
14	EFEC. MOISTURE OF COARSE AGGREGATES (%) (ONE RELATION FOR EACH TYPE OF COARSE AGGREGATE USED)	AMOUNT OF COARSE AGGREGATE (Kg)
15	EFECTIVE MOISTURE OF FINE AGGREGATE.(%) (ONE RELATION FOR EACH TYPE OF FINE AGGREGATE USED)	AMOUNT OF FINE AGGREGATE (KG)
16	FLY ASH / (CEMENT+ FLY ASH)	28-D COMPRESSIVE STRENGTH (Mpa)
17	CONCRETE TEMPERATURE	28-D COMPRESSIVE STRENGTH (Mpa)
18	ADDED MIXTURES (Ml/M3)	MIXING WATER(L/M3)

TABLE 3-2 RELATIONSHIPS CONSIDERED BY THE MODEL

OBJECTIVE FUNCTION

The objective function describes the measure of performance for the optimization model. The model considers the minimization of the cost as the objective function. This objective function can be written as

$$Min\, Z = \sum_{i=1}^{n} ING_i * COST_i$$

Where

Z = cost of concrete mix (\$/m3)

ING_i = amount (Kg/m3) of ingredient i. i=1...n(n=number of concrete ingredients)

$COST_i$= cost (\$/Kg) of ingredient i. i=1...n(n=number of concrete ingredients)

CONSTRAINTS FOR THE OPTIMIZATION MODEL

To include the relationships mentioned before three types of constraints were developed: continuous variables constraints, discrete variables constraints and zero-one variables constraints.

1. Continuous Variables Constraints

Upper and lower constraints defining the boundaries of the band that contains the historical data corresponding to any two variables are derived. The trend (slope) of such band should be the commonly known trend for the relation between the two variables. To develop these constraints, a linear regression was applied to the uppermost and lowest sets of points, respectively, which maintain the required trend of the relationship.

Maximum and minimum values of both the dependent and independent variables (from historical data) are added to establish the limits on the application of the developed relationships. Figure 3-1 shows the feasible region obtained after applying the upper and lower limits as well as the maximum and minimum limits.

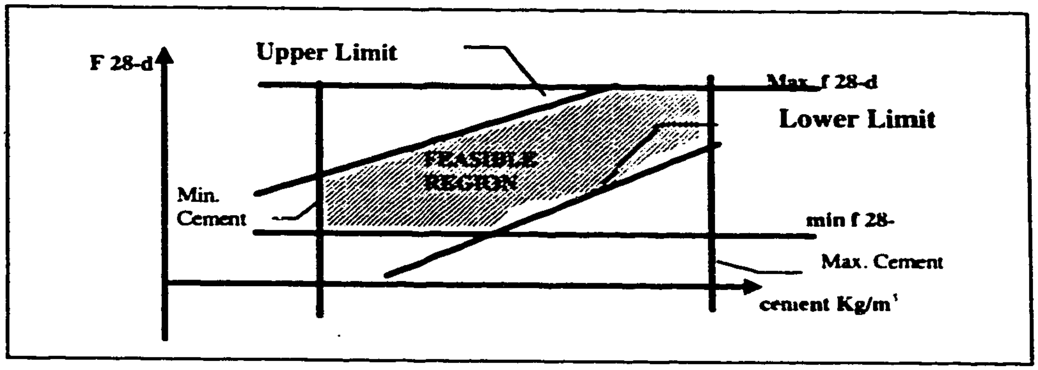

FIGURE 3-1 FEASIBLE REGION AFTER APPLYING UPPER LIMIT, LOWER LIMIT, MAXIMUM AND MINIMUM VALUES

Continuous variables constraints for each relation (table 3-2) can be written as

$$DEP_k \leq UL_k * IND_k + CU_k$$
$$DEP_k \geq LL_k * IND_k + CL_k$$
$$DEP_k \geq Min(DEP_k)$$
$$DEP_k \leq Max(DEP_k)$$
$$IND_k \geq Min(IND_k)$$
$$IND_k \leq Max(IND_k)$$

Where

DEP_k = dependent variable for relationship k. k=1...m (m = number of relationships)

IND_k = independent variable for relationship k. k=1...m (m = number of relationships)

UL_k = upper limit slope for relation k.

CU_k = upper limit constant for relation k.

LL_k = lower limit slope for relation k.

CL_k = lower limit constant for relation k.

If either or both of the two variables have specified values (from the mix's specifications), then such values are added to the set of relationships shown in Fig 3-5. For example, if specified 28-days strength is 25 MPa then a constraint describing such requirement can be written as follows: f28-d >= 25 MPa. The feasible region, shown in Figure 3-1 will then be further reduced by the introduction of the new constraint as shown in Figure 3-2.

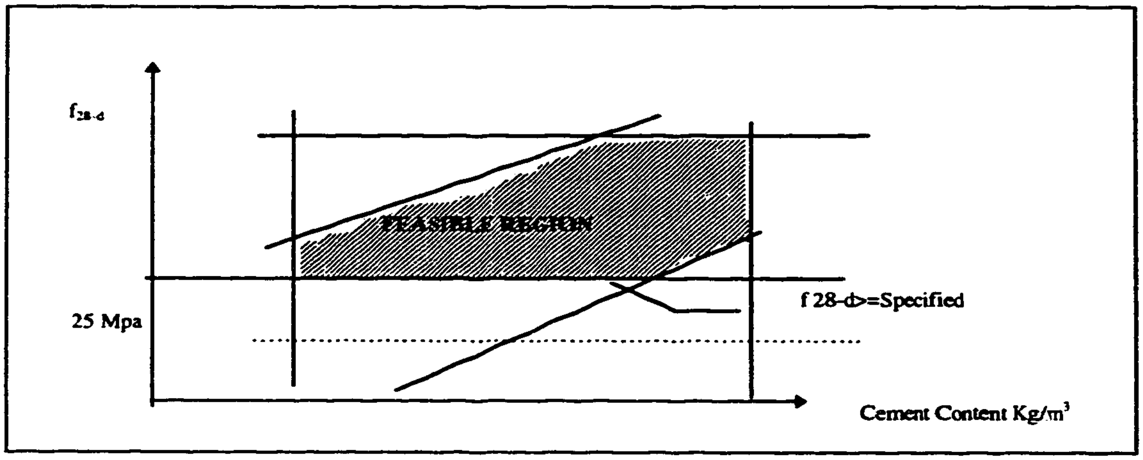

FIGURE 3-2 FEASIBLE REGION AFTER APPLYING SPECIFIC REQUIREMENTS

2. Discrete Variables Constraints

Some relationships imply the division of two continuous variables which would lead to the formulation of a non-linear model. In order to avoid this non-linearity discrete values were assigned to each of such variables. These discrete values are selected depending on the range between the maximum and minimum values obtained from historical data.

For a relationship that requires as one of its variables the division of two other variables (VARY/VARX) discrete variables constraints can be written as

$$VARX = \sum_{j=1}^{n+1} \left(\frac{(Max.\ VARX - Min.\ VARX)}{n} * (n-1) + Min.\ VARX \right) X_j$$

$$VARY = \sum_{i=1}^{m+1} \left(\frac{(Max.\ VARY - Min.\ VARY)}{m} * (m-1) + Min.\ VARY \right) Y_i$$

$$(VARY\ /\ VARX) = \sum_{i=1}^{m+1} \sum_{j=1}^{n+1} \left(\frac{\left(\frac{(Max.\ VARY - Min.\ VARY)}{m} * (m-1) + Min.\ VARY \right)}{\left(\frac{(Max.\ VARX - Min.\ VARX)}{n} * (n-1) + Min.\ VARX \right)} \right) Z_{ij}$$

Where

VARX= variable expressed in terms of discrete values from historical data.

Max. VARX and Min.VARX are the maximum and minimum values from historical data of variable VARX.

n = selected number of discrete values between the maximum and minimum values of historical data for variable VARX. The number of discrete values is selected by the user.

X_j = 0/1 variable associated with the jth discrete value of variable VARX. (j= 1....n)

VARY= variable expressed in terms of discrete values from historical data.

Max. VARY and Min.VARY are the maximum and minimum values from historical data for variable VARY.

m = selected number of discrete values between the maximum and minimum values of historical data for variable VARY. The number of discrete values is selected by the user.

Y_i = 0/1 variable associated with the ith discrete value of variable VAR (i= 1....m)

Z_{ij} = 0/1 variables associated with each discrete value of the VARY/VARX ratio.

3. Zero - One Variables Constraints:

When a particular value for a (VARY/VARX) ratio is selected, among the possible discrete values, the corresponding discrete values for both VARX and VARY must also be selected. To do this, the zero-one variables (Z_{ij}) associated with (VARY/VARX) ratio are linked to the zero-one variables (X_j and Y_i) for both VARX and VARY by developing the following constraints:

$$\sum_{j=1}^{n+1} Zij = Y_i \quad (i=1.... m+1)$$

$$\sum_{i=1}^{m+1} Zij = X_i \quad (j=1....n+1)$$

To ensure that only one discrete value for VARX, VARY and VARY/VARX ratio is selected, the following condition is included:

$$\sum_{j=1}^{n+1} X_j = 1 \text{ or}$$

$$\sum_{i=1}^{m+1} Y_i = 1$$

DATA MODELING

One of the main characteristics of the model is its ability to reflect the conditions founded at a particular plant. This will guarantee that the mix provided by the model will be optimum for these local conditions. Historical data (mixes designed previously) includes information about the amounts and the ingredients used as well as the test results for the quality control parameters (compressive strength, slump and air content). In order to give consistency to the model, the historical information used have the following characteristics: 1) actual batched amounts of ingredients were considered and 2) test results considered for the quality control parameters (slump, air content andcompression strength) were the on-site test results.

The mixes manufactured in the past (historical information) can be organized or categorized in such a way that the model can be used to produce mixes that meet specific conditions and characteristics. With this in mind the historical information can be organized according to the following parameters:

- Construction season
- Mix use
- Specified compressive strength
- Specified curing age
- Specified cement type
- Specified aggregate size
- Specified slump
- Specified air content
- Source for fine aggregates
- Source for coarse aggregates

MANIPULATION OF THE MIX INFORMATION

In order to facilitate the manipulation (storing and retrieving) of the information about the mixes previously designed a relational database was created. A relational database allows the inclusion of several tables that can be linked to each other in a way that entering and retrieving information can be done in a very efficient way. Figure 3-3 shows the structure of the database created to store all the mix information. In essence the fields for this database are the parameters mentioned above. (construction season, mix use, compressive strength etc.) Due to space availability only few fields are displayed.

FIELD

MIX ID	DATE OF DESIGN	SLUMP	STRENGTH	AIR CONTENT	CEMENT
001	10/20/93	80	25	2	400
002	11/12/93	60	30	1.5	500
003	11/10/93	80	25	2	600
004	12/12/93	90	30	1.0	400

RECORD

FIGURE 3-3 MIX DATABASE STRUCTURE

Once the information is in the database retrieving the mixes that match specific characteristics is an easy task.

At this stage and with the available tools in terms of software using the model to produce an optimum mix will involve the following steps:

1. Retrieve from the database all the mixes that match the specified requirements.
2. Develop the relationships for these set of data (table 3-2). This can be done by using software with statistical and graphical capabilities.
3. Build the model with the relationships developed in step 2.
4. Solve the model. This can be done by using commercial software to solve linear programming problems.
5. Send the results to the batching plant.

PROGRAMMING IMPLEMENTATION

The amount of information and work required to build and actually use the results provided by the model are considerable. This by itself justifies the automation of the whole process. Another aspect to point out is the fact that if the model is adopted then every time a new mix is designed a new record will be added to the historical information. This means that the relationships initially developed could change with time. Therefore automation of the process is required if the dynamic nature of the problem wants to be handled in a proper and efficient way.

The inconveniences mentioned before motivated the development of a programming application. A programming application that facilitates the use of the mathematical model by the user was developed. A detail description about the system and its main feature are described in the following sections.

DESCRIPTION OF THE SYSTEM

A computer program for windows environment was developed. This program was written using MS Visual Basic 3.0 which is a event driven programming language. One of the main features of this program is that it allows the user to develop the relationships in a very efficient way. A friendly graphical interface gives the user the opportunity to evaluate and analyze different possibilities for an specific relationship before adopting a final decision. The system consists of three main components: a linear programming software (LINDO); the mix design program (Visual Basic Program) and an historical database. This structure is depicted in Figure 3-8. Once the input for a new mix design has been entered the mix program will retrieve all the historical mixes from the historical table.

Then the relationships are developed and the model is generated. At this point LINDO is invoked and the mathematical model is solved. The answers generated by LINDO are sent back to the mix program to generate the mix report and to update the historical database.

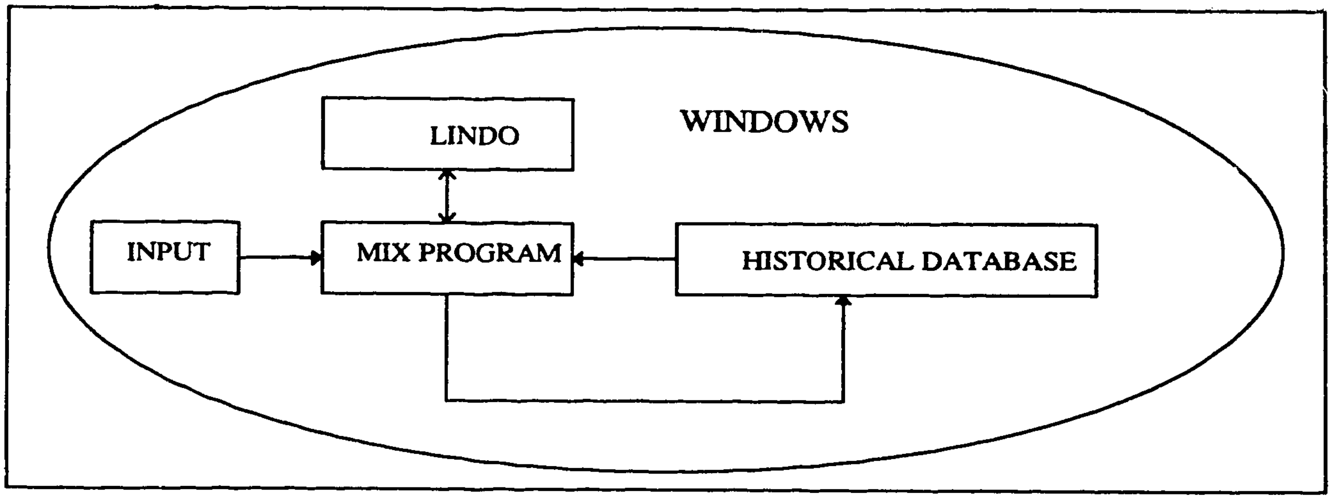

FIGURE 3-4 SYSTEM STRUCTURE

The program provides the following :

- Allows the entering of the input data through a friendly user interface.
- Storing and updating historical data when required.
- Automatic development of relationships.
- Automatic generation of the model.
- Automatic interpretation of optimization results and the generation of reports
- Interaction with other processes related to mix design such as delivery and batching.

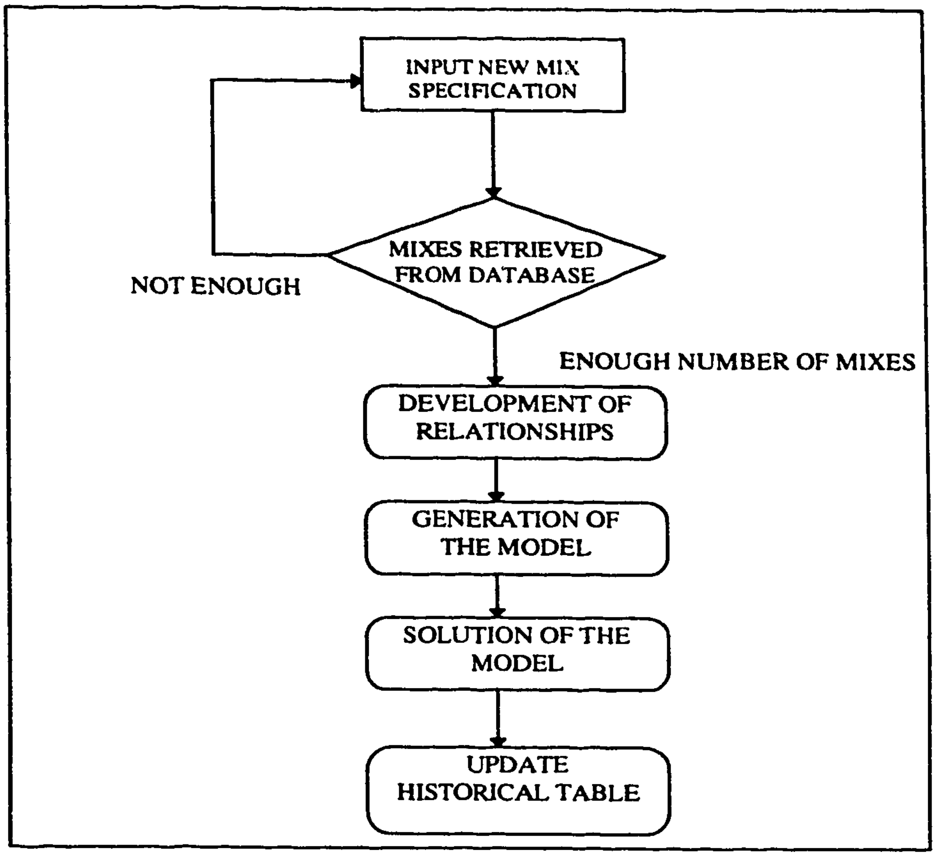

FIGURE 3-5 FLOW DIAGRAM SHOWING OPERATION OF THE SYSTEM

The operation of the system is summarized in Figure 3-5. The computer program has three main modules. The first module retrieves from the historical table the mixes that match the input specifications entered by the user. The second module is the graphical interface that allows the user to develop the required relationships for the mixes retrieved. The third module generates and solve the model based on the relationships developed.

Module 1- Input new mix specifications and retrieval from historical database

This module acquires the information required for the new mix. Figures 3-6, 3-7 and 3-8 show the windows used to enter this information.

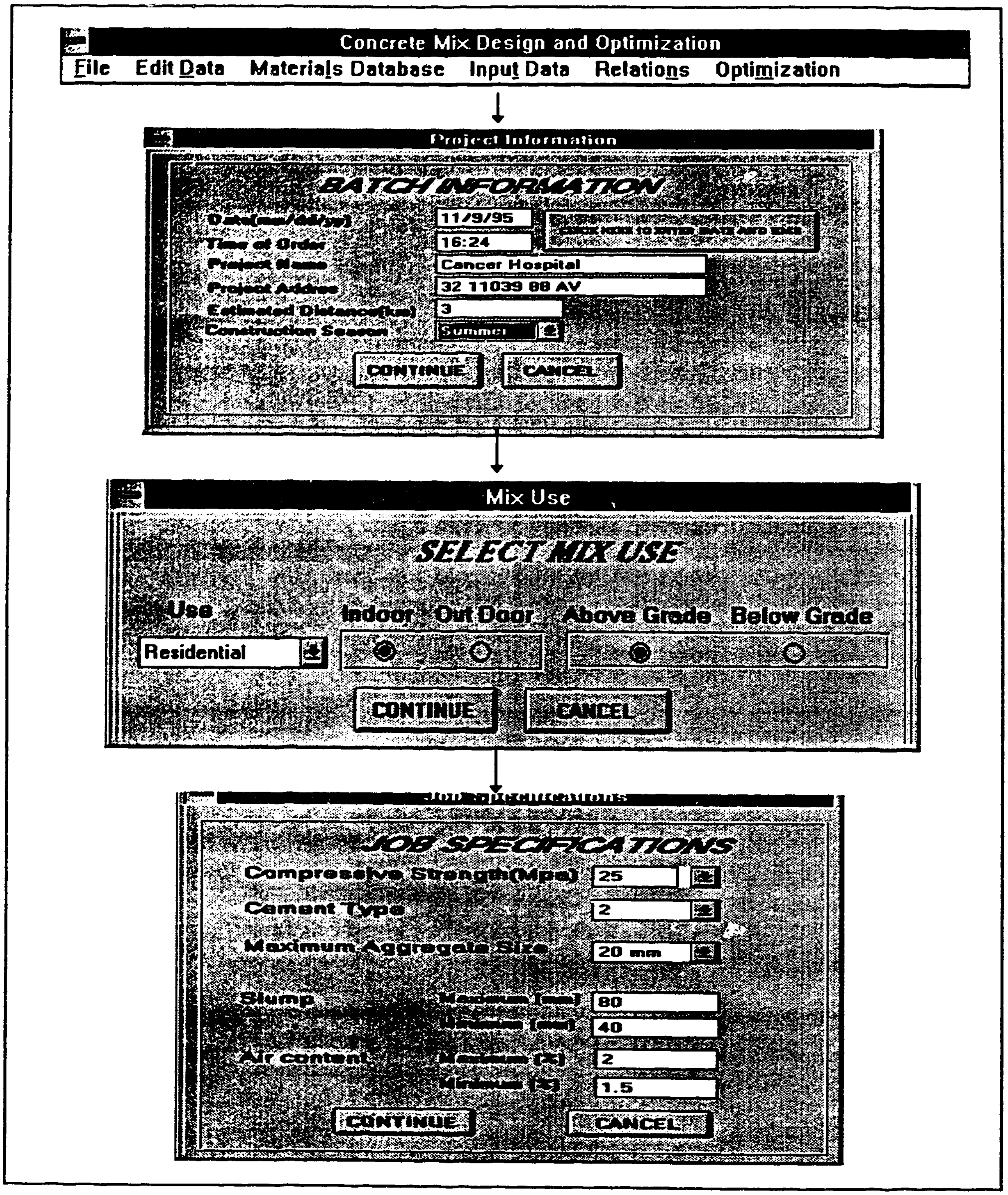

FIGURE 3-6 SCREEN S USED TO ENTER INFORMATION REGARDING MIX USE AND MIX SPECIFICATIONS

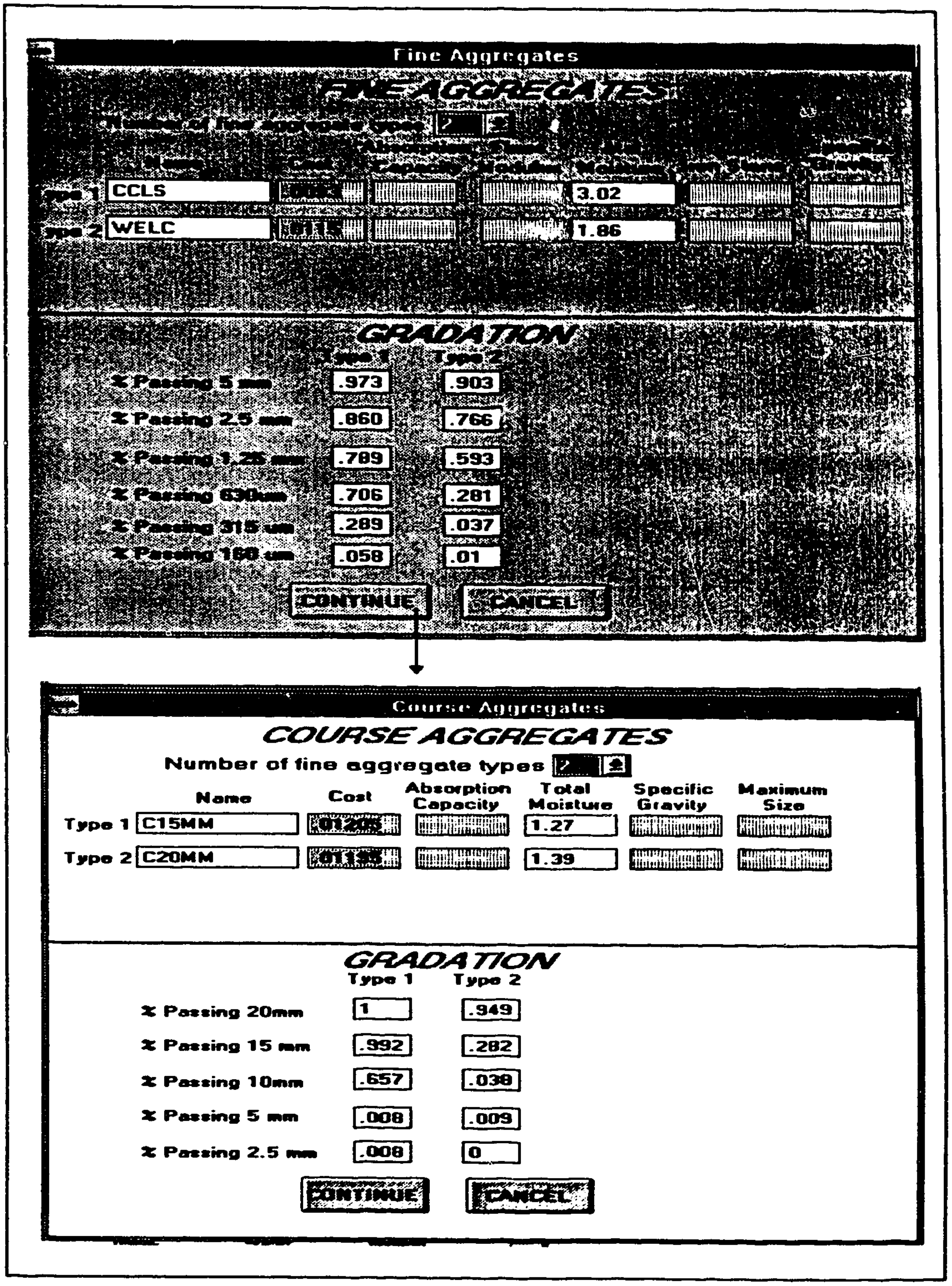

FIGURE 3-7 SCREEN S USED TO ENTER INFORMATION REGARDING AGGREGATES

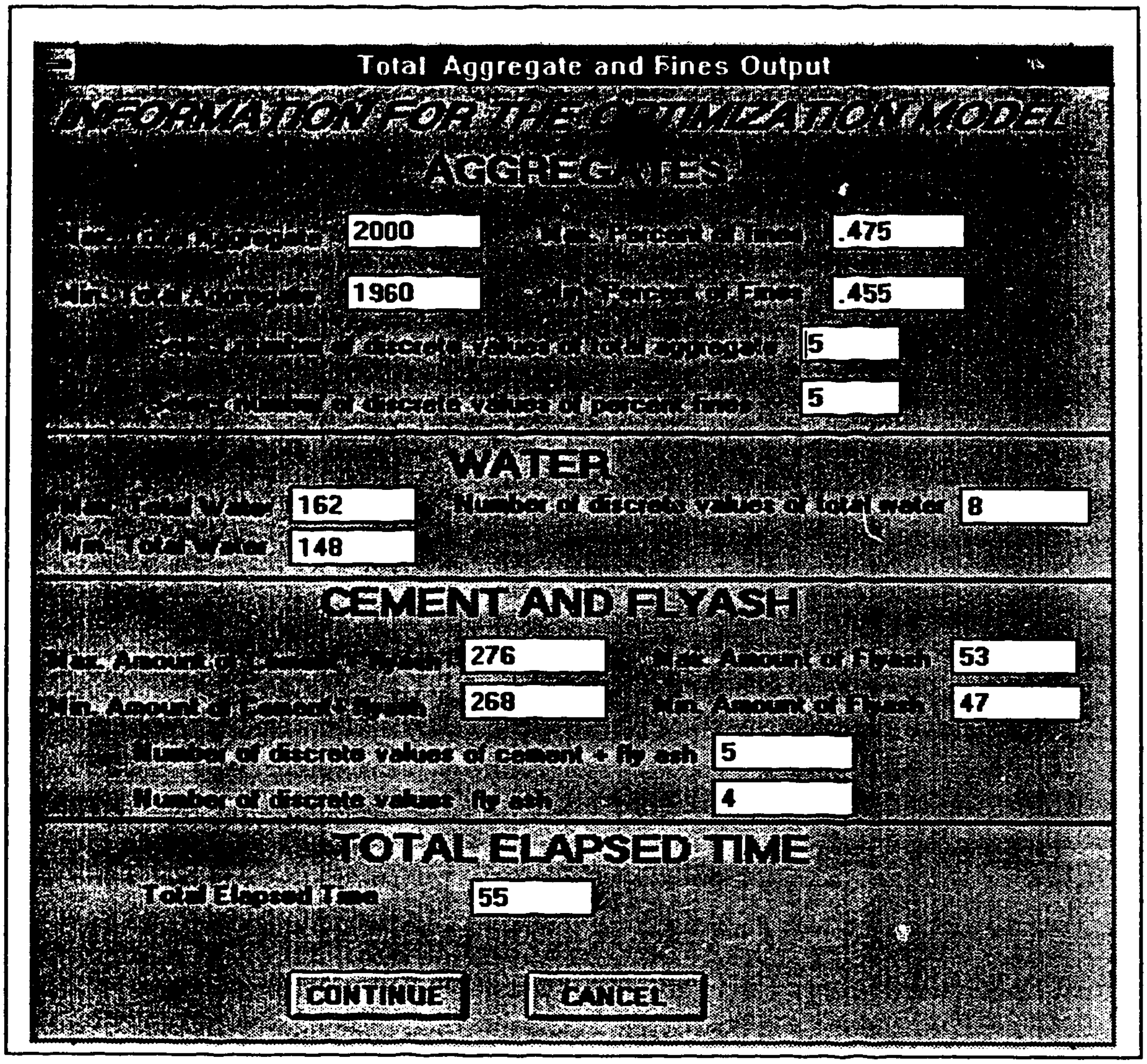

FIGURE 3-8 SCREEN USED TO ENTER INFORMATION ABOUT THE DISCRETE VARIABLES

These windows correspond to the general batch information, the mix use, mix technical specifications, aggregates specifications and information about the discrete variables used by the model. Once all the requirements have been provided by the user the program retrieves all the mixes that meet these specifications from the historical table. These mixes (records) are stored in a table that has the same structure the historical table has. This table is going to be accessed later to develop the relationships.

Module 2- Graphical interface to develop relationships

This module allows the user to automatically develop the relationships. Figure 3-9 shows the interface designed for this purpose. This window displays in a textual way the mixes founded by module 1. It also shows the parameters values (slope and constant) that define the upper and lower limits for each relationship as well as the maximum and minimum values the independent and dependent variables have.

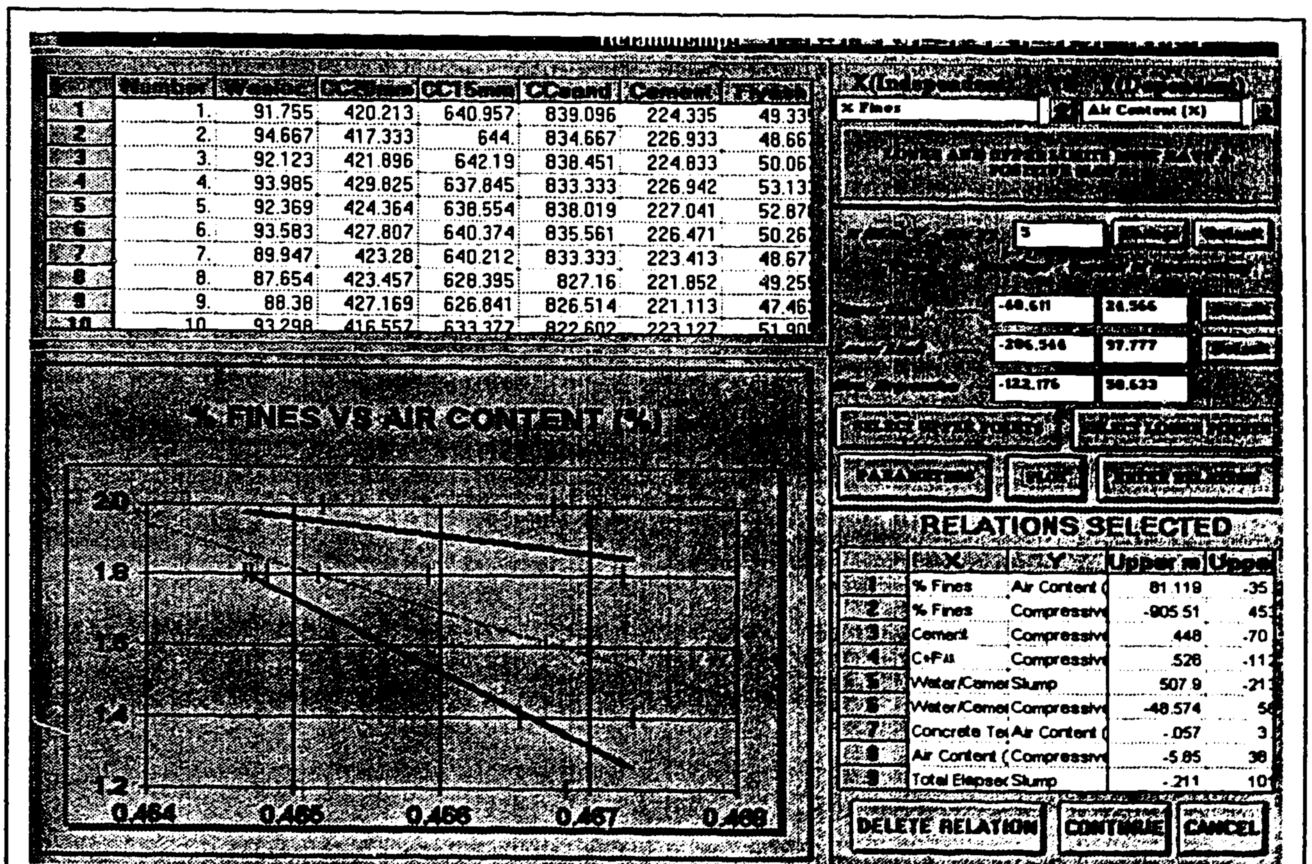

FIGURE 3-9 INTERFACE TO DEVELOP THE RELATIONSHIPS

To develop a relationship the following steps have to be done:

1. The independent and dependent variables for the relationship must be selected. This is done by clicking and selecting on the independent and dependent variables boxes placed in the upper right corner of the window.

2. Definition of upper and lower limits. The definition of the upper and lower limits can be obtained in three different ways:

   a) The program will suggest the upper and lower limits by default. Initially a linear regression takes place considering all the data. Then the program automatically selects the points considered to develop the upper and lower limits. Once these points are selected a linear regression for each limit is performed. This selection is done by comparing each data point's ordinate with the value obtained using the regression derived for all the data points (see Figure 3-10). If the difference is positive and greater than certain value (5% of the difference between the maximum and the minimum ordinate values for the set of data) the point will be taken to develop the upper limit. If the difference is negative and smaller than certain value (same as before) the point will be taken to develop the lower limit. This difference that by default is 5% can be changed by the user. The main idea is to consider the uppermost and lowest sets of points. To obtain these initial relationships the user just has to click on the plot option. The limits as well as the data points will be displayed in a graph.

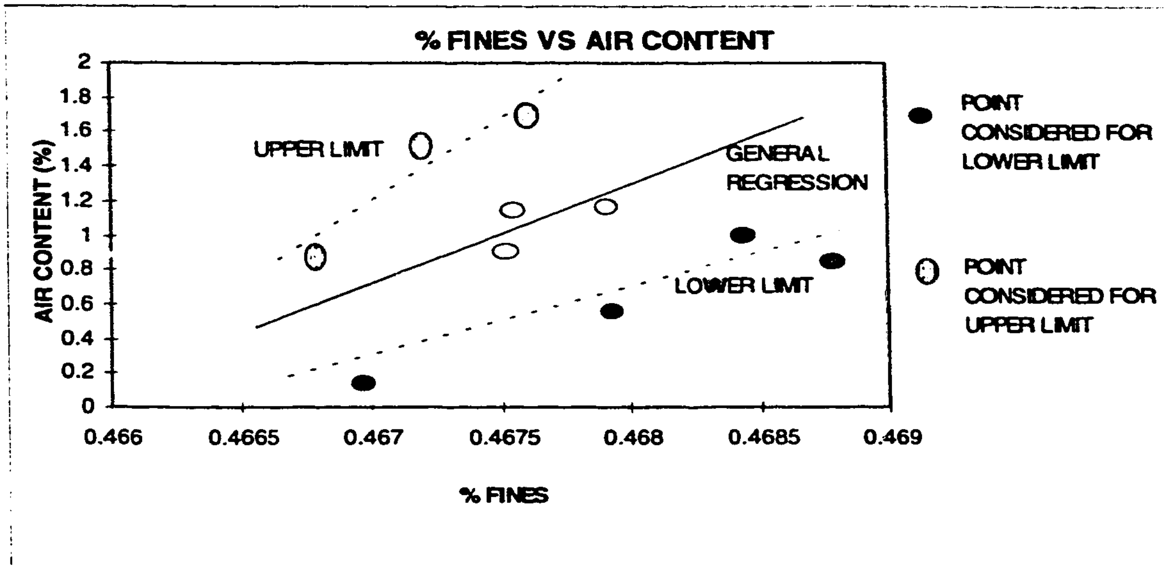

FIGURE 3-10 SELECTOIN OF POINTS TO DEFINE UPPER AND LOWER LIMITS

b) The user selects the points for the upper and lower limits. The user can select the points he/she wants to consider. To do this the user has to click on the selection of upper/lower points option. Then the points can be selected by clicking on them in the graph. Once this is done the plot button must be selected to display the new limits.

c) Changing the parameters values. The user can specify the parameter values (slope and constant) for the limits. This can be done by changing the values for the parameters. All the user has to do is to enter the values he/she wants.

3. Once the user feels that the relationship he/she is working with, is appropriate then this relationship will be selected and used to feed the mathematical model. This is done by clicking on the enter relation button. The grid placed on the lower right corner of the window (Figure 3-9) displays the parameters values for the relationships developed. The

information about the relationships (contained in the grid) is stored in a database. Figure 3-11 shows the structure of this database.

X	Y	SLOPE U.L.	SLOPE L.L.	CONST. U.L.	CONST. L.L.	MAX X	MAX. Y	MIN. X	MIN. Y

X= INDEPENDENT VARIABLE (CEMENT, WATER ETC.)

Y= DEPENDENT VARIABLE (STRENGTH, TEMPERATURE ETC.)

SLOPE U.L. = SLOPE FOR THE UPPER LIMIT

SLOPE L.L. = SLOPE FOR THE LOWER LIMIT

CONST. U.L. = CONSTANT FOR THE UPPER LIMIT

CONST. L.L. = CONSTANT FOR THE LOWER LIMIT

MAX. X = MAXIMUM VALUE FOR THE INDEPENDENT VARIABLE

MIN. X = MINIMUM VALUE FOR THE INDEPENDENT VARIABLE

MAX. Y = MAXIMUM VALUE FOR THE DEPENDENT VARIABLE

MIN. Y = MINIMUM VALUE FOR THE DEPENDENT VARIABLE

FIGURE 3-11 DATABASE TO STORE RELATIONSHIPS

Module 3- Generation and solution of the model

The model is generated from the database that contains all information about the relationships. A text file that will be the input for LINDO is generated. Then LINDO is invoked and the model is solved. Once the model is solved a report is generated. This report can be seen in Figure 3-12. Lindo is a software for linear programming, mixed integer linear programming and quadratic programming. It uses simplex and active set algorithms for linear and quadratic programming, and a branch-and-bound approach for mixed integer programming.

The student version of LINDO can handle up to 100 constraints and 200 variables, while the extended version of LINDO handles up to 32000 constraints and 100000 variables.

The PC version includes a full-screen editor and a pop-up window that allows the progress of the algorithm to be monitored.

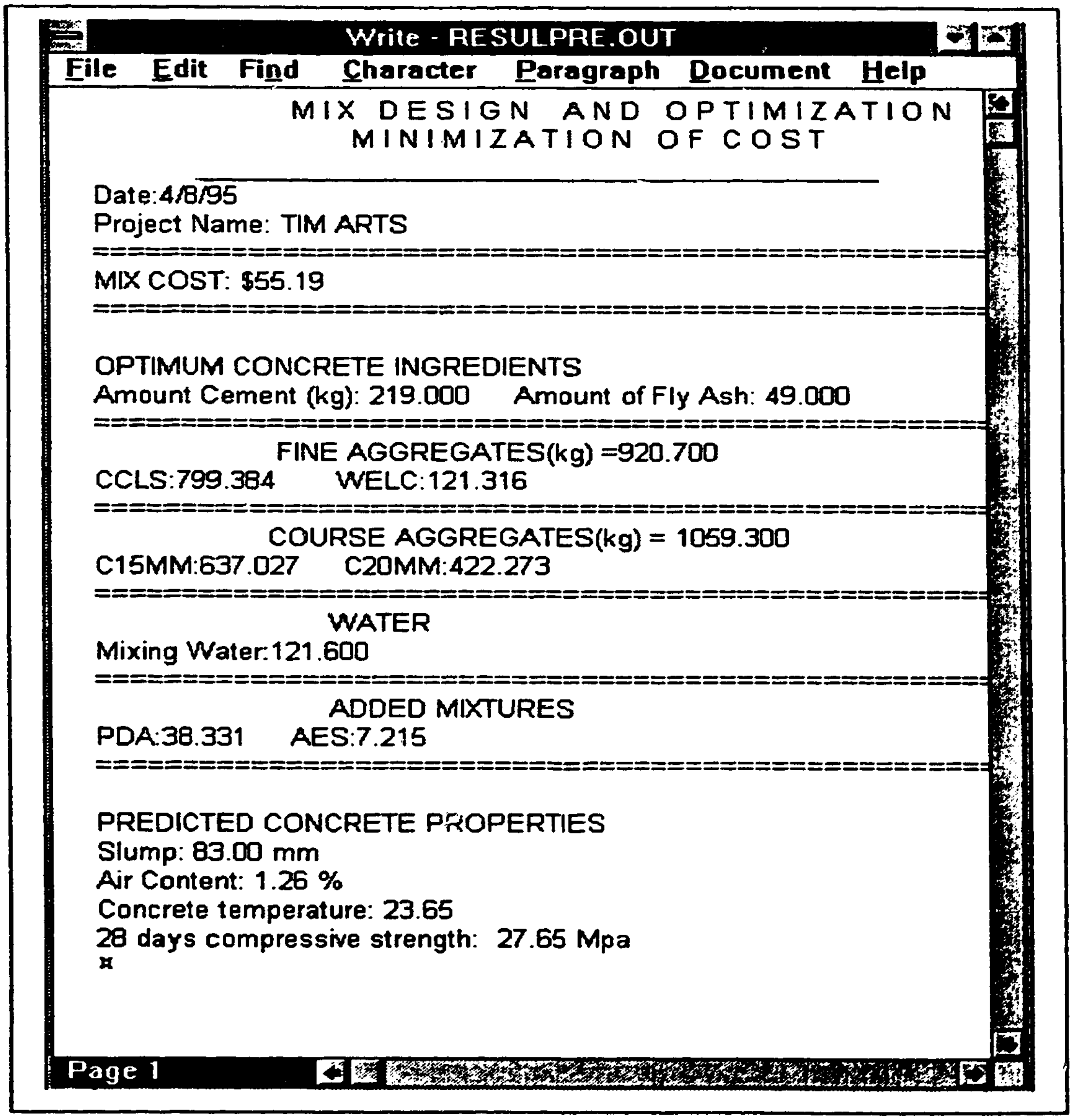

FIGURE 3-12 OPTIMIZATION RESULTS

CASE STUDY

The program is used to design a mix with certain specifications. This design is done using the program developed. A mix with the following specifications is required:

a) 28- days strength :25 Mpa
b) slump : 80 mm
c) no air
d) maximum aggregate size: 20 mm
e) type of cement : 10 + fly ash
f) use: slabs
g) season : winter

When the user runs the program a main menu is displayed. Figure 3-13 displays the main menu. In general the main menu gives the user the following options:

- Editing the current input information before optimization is carried
- Updating the materials database
- Inputting data for a new mix design
- Optimizing: the mix cost

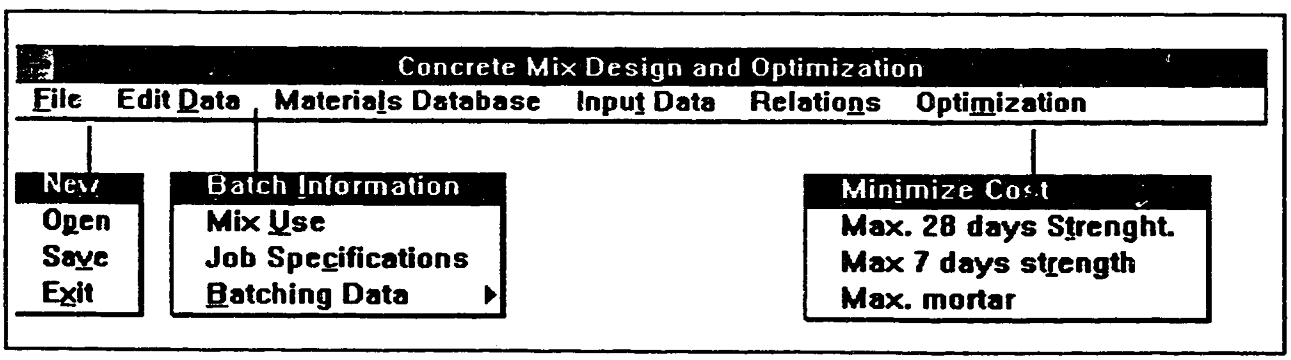

FIGURE 3-13 MAIN MENU

The next step is to enter all the information about the mix to be designed. To do this the user has to select the input data option in the main menu. He/she will be asked about the mix design requirements, materials and materials gradation. (Figures 3-6, 3-7 and 3-8)

Eleven mixes were identified from the historical data. Appendix A presents (after adjusting for batching) and actually batched quantities of concrete ingredients for the eleven mixes per cubic meter. The same appendix also presents the quality control test results.

The next step is to develop the relationships by using the graphical interface described before. This graphical interface is obtained by selecting the relations option in the main menu. Once the relationships have been defined the final step is to do the optimization by clicking on the optimization option. At this point the model will be generated and solved. (appendix B and C show the relationships developed and the mathematical model)

Validation of the model

The validation of the model was done by solving the mathematical model for each one of the eleven mixes. Figures 3-14 to 3-19 show the actual and the optimum ingredients amounts as well as the actual and minimum mix cost for each of these eleven mixes.

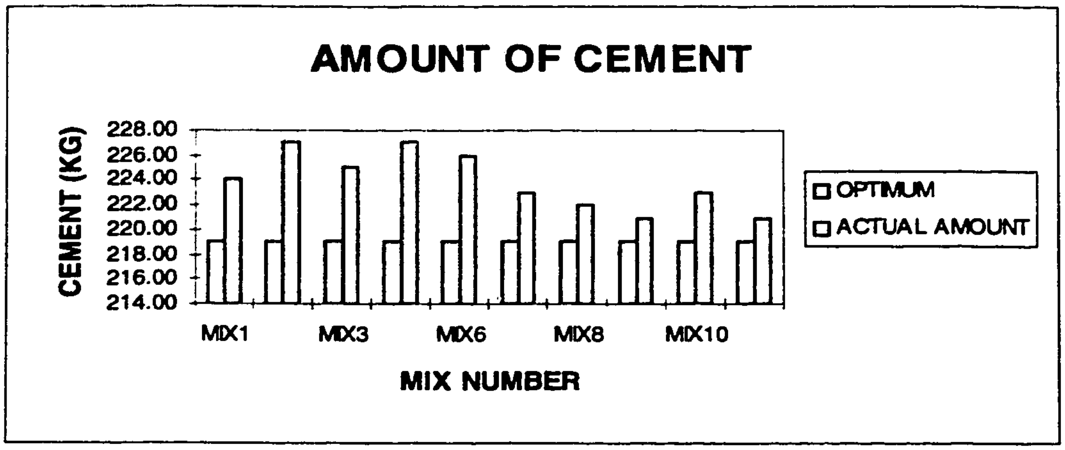

FIGURE 3-14 AMOUNT OF CEMENT

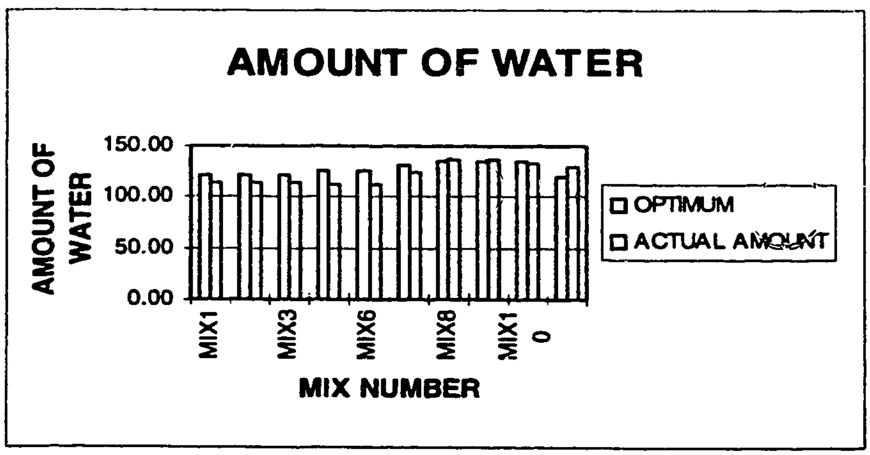

FIGURE 3-15 AMOUNT OF WATER

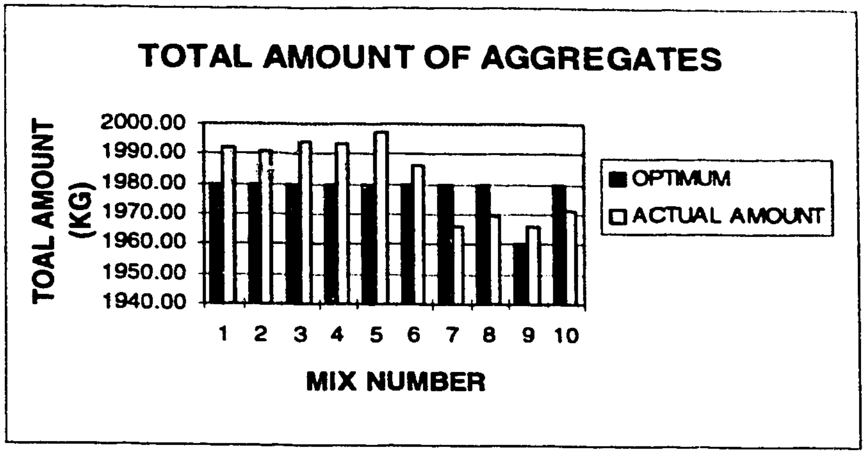

FIGURE 3-16 TOTAL AMOUNT OF AGGREGATES

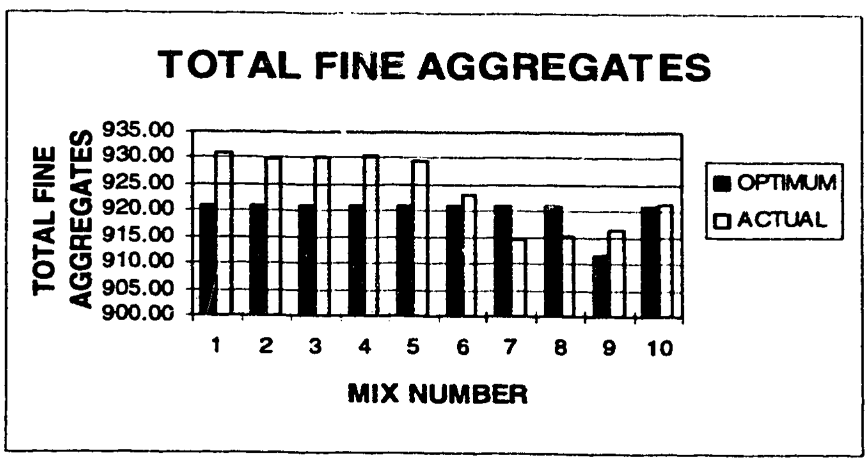

FIGURE 3-17 TOTAL AMOUNT OF FINE AGGREGATES

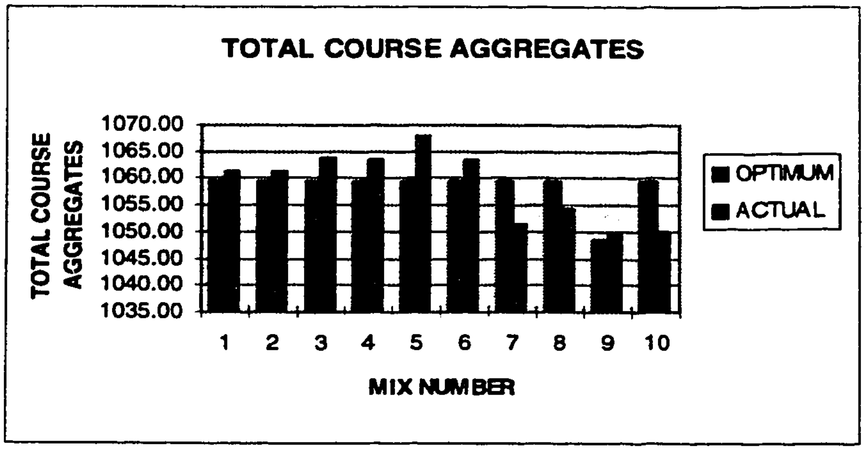

FIGURE 3-18 TOTAL COARSE AGGREGATES

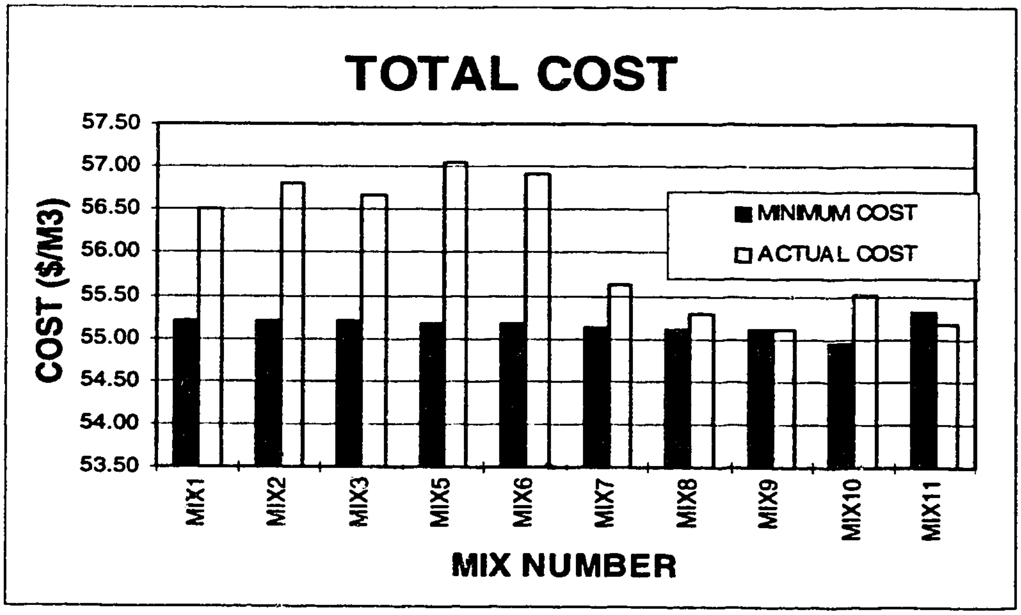

FIGURE 3-19 TOTAL COST

Figure 3-19 compares the actual costs of these mixes and the cost obtained by the model. This figure demonstrates how the proposed process may result in a cost saving to a ready-mix concrete plant since the minimum cost is less than the actual cost in most of the eleven mixes. The objective function is to minimize the cost of the mix which means that the cost obtained by the model should always be smaller than the actual cost. However this is not the case for mix 11 (Figure 3-19). This apparent inconsistency will be explained in the following section. Figures 3-14 to 3-19 also show as a general trend that the ingredients amount provided by the model are smaller than the actual amounts (see also appendix D).

Limitations of the model

The number of discrete values selected for the discrete variables (Figure 3-8) can affect the results provided by the model. In the previous section it was pointed out that the minimum cost obtained for one of the mixes (mix 11) was larger than the actual cost (minimum cost= $55.32, actual cost= $55.18). The reason for this apparent inconsistency is that the intervals selected for the discrete variables are too large that the model cannot select better solutions that might be inbetween. The solution to this limitation is to increase the number of discrete values for the discrete variables.

The optimum total amount of aggregates for this mix is larger than the actual amounts (Figure 3-16). On the other hand, Figure 3-15 shows that the optimum and actual amounts of water are very close. This indicates that for this specific mix (mix 11) the discrete values selected for the aggregates and for water will affect the cost provided by the model. If more discrete values for the aggregates and water are selected then the cost provided by the model should decrease as demonstrated in Table 3-3. The minimum cost of $54.94 is lower than the actual which was $55.18 thus demonstrating that it is an improvement over the initial condition.

NUMBER OF DISCRETE VALUES FOR TOTAL AGGREGATES	NUMBER OF DISCRETE VALUES FOR PERCENT OF FINES	NUMBER OF DISCRETE VALUES FOR TOTAL WATER	MINMUM COST GIVEN BY THE MODEL
5	5	8	$ 55.32
6	5	8	$ 55.27
7	5	8	$ 55.23
7	7	10	$ 54.97

TABLE 3-3 MINIMUM COST OBTAINED FOR DIFFERENT NUMBER OF DISCRETE VALUES

Another limitation can arise from the non linearity of some relationships such as water/cement ratio vs. strength. This was handled by discretizing certain values. In fact, it has been assumed is that the data considered are within a small range that this relationship can be considered as linear. However, in some cases this might not be true. For example, assume that the data obtained from the historical information for water/cement vs. strength looks like Figure 3-20. Developing the upper limit will over estimate the strength and obviously this can be a serious problem. This obstacle can be overcome using small linear segments to represent the curve (Figure 3-20).

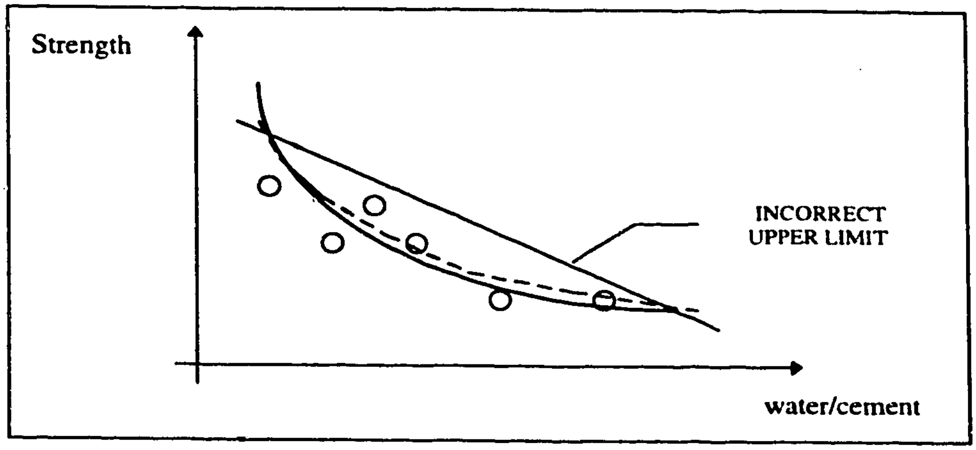

FIGURE 3-20 NON LINEARITY OF RELATIONSHIPS

CONCLUDING REMARKS

This paper presented a computerized implementation for a linear formulation of the mix design problem. The system integrates all the systems required to solve the problem in such a way that the user only has to deal with one general system. Its flexibility also allows to experiment and try different scenarios before making a final decision.

Features such as the automatic generation and solution of the model makes possible to use mathematical models in actual life. With an approach like the one discussed in this paper the construction practitioner does not have to know in detail all the theory about mathematical programming. Because of its flexibility the system can also be implemented in different organizations.

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APPENDIX A: INGREDIENTS AMOUNTS FOR THE ELEVEN MIXES

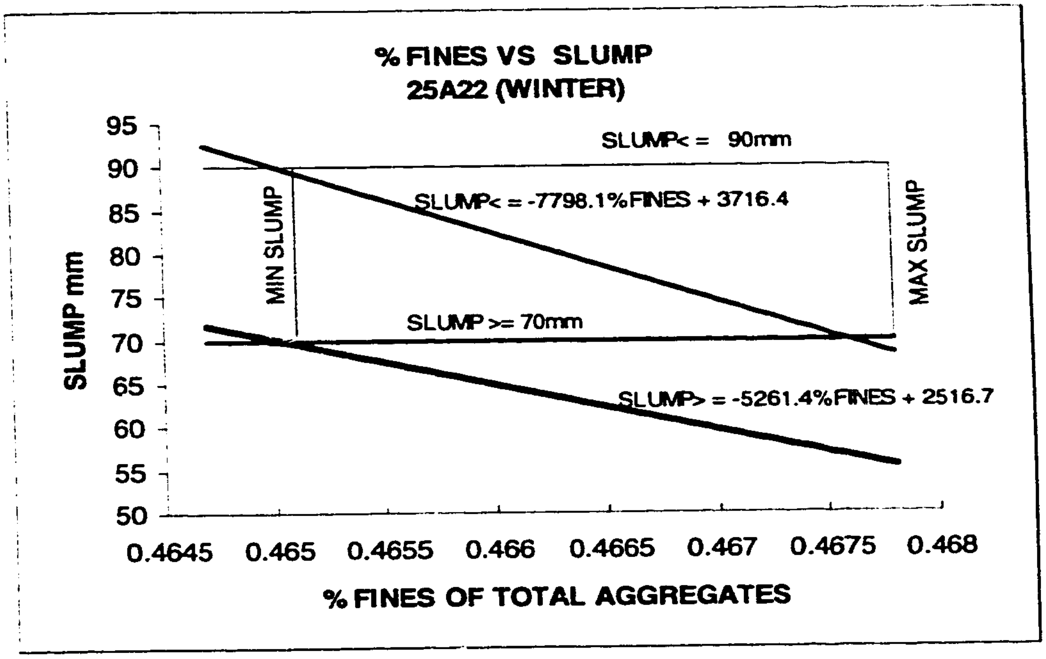
	Weslox(Coarse Sand)		CC20mm(Coarse Aggregate)		CC15mm(Coarse Aggregate)		CCsand(Fine Sand)		Cement		Flyash		Water		Water Reducer(AES)		Accelerator(PDA 304)	
Mix No	Design	Batched	Design	Batched	Design	Batched	Design	Batched	Design	Batched	Design	Batched	Design	Batched	Design	Batched	Design	Batched
1	92.12	91.76	421.90	420.21	642.19	640.96	833.11	839.10	225.37	224.34	50.07	49.34	114.69	114.36	10.41	10.37	38.45	38.30
2	92.25	94.67	422.46	417.33	643.05	644.00	834.22	834.67	225.67	226.93	50.13	48.67	113.77	114.00	10.43	10.40	38.50	38.40
3	92.37	92.12	423.03	421.90	643.91	642.19	835.34	838.45	225.97	224.83	50.20	50.07	112.99	113.08	10.44	10.41	38.55	38.45
4	92.96	93.98	425.88	429.82	639.45	637.84	837.94	833.33	226.13	226.94	50.25	53.13	111.93	114.91	10.55	10.53	38.69	38.60
5	92.49	92.37	426.27	424.36	639.41	638.55	837.80	838.02	226.27	227.04	50.27	52.88	111.93	112.18	10.46	10.44	38.61	38.55
6	92.49	93.58	426.27	427.81	639.41	640.37	837.80	835.56	226.27	226.47	50.27	50.27	111.93	111.90	10.46	10.43	38.61	38.50
7	91.63	89.95	419.65	423.28	637.45	640.21	835.33	833.33	224.17	223.41	49.80	48.68	122.71	122.62	6.91	6.88	38.25	38.10
8	90.46	87.65	417.60	423.46	630.73	628.40	826.52	827.16	223.05	221.85	49.57	49.26	136.18	135.80	6.94	6.91	38.17	38.15
9	90.76	88.38	417.49	427.17	628.71	626.84	826.73	826.51	222.77	221.11	49.50	47.46	135.97	136.17	6.93	6.87	38.12	37.81
10	91.03	93.30	416.89	416.56	629.29	633.38	828.50	822.60	222.69	223.13	49.47	51.91	132.72	132.19	6.86	6.83	37.99	37.84
11	91.32	94.22	420.09	417.93	631.66	632.22	828.01	826.75	222.68	220.82	49.47	49.85	128.46	128.88	6.85	6.84	38.05	37.84

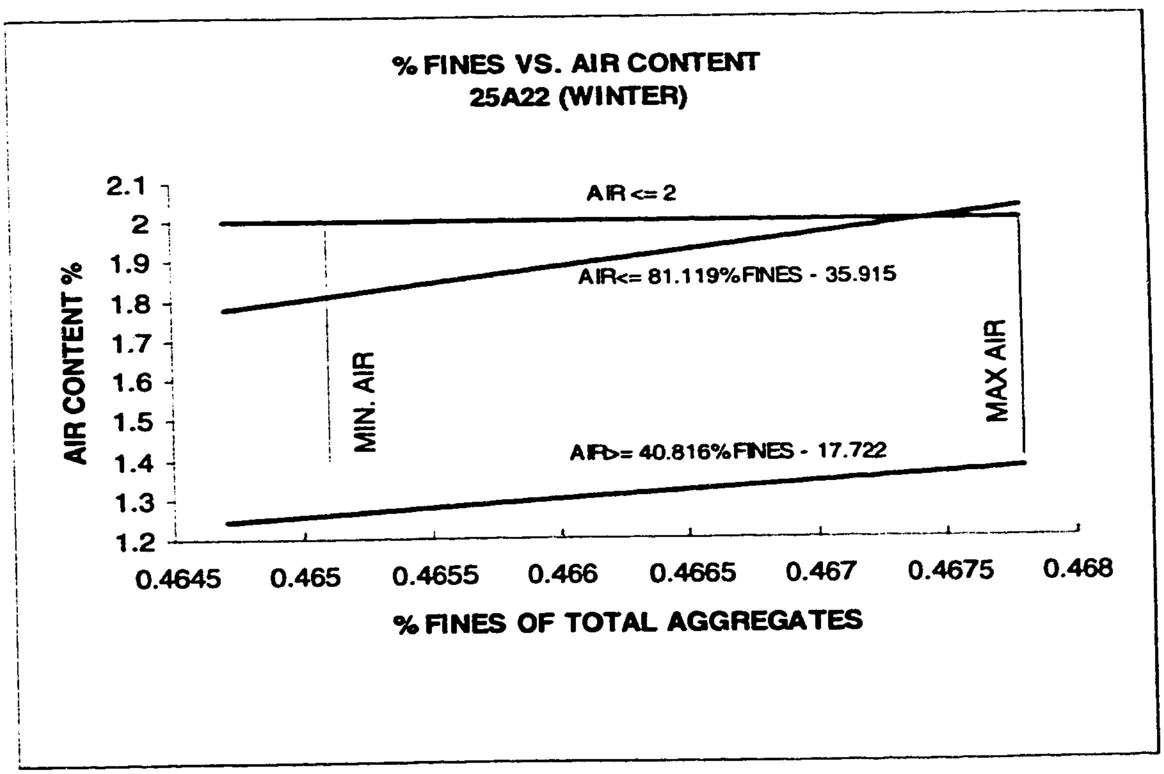
TABLE A-1 DESIGNED AND ACTUAL QUANTITIES FOR THE SELECTED 11 MIXES

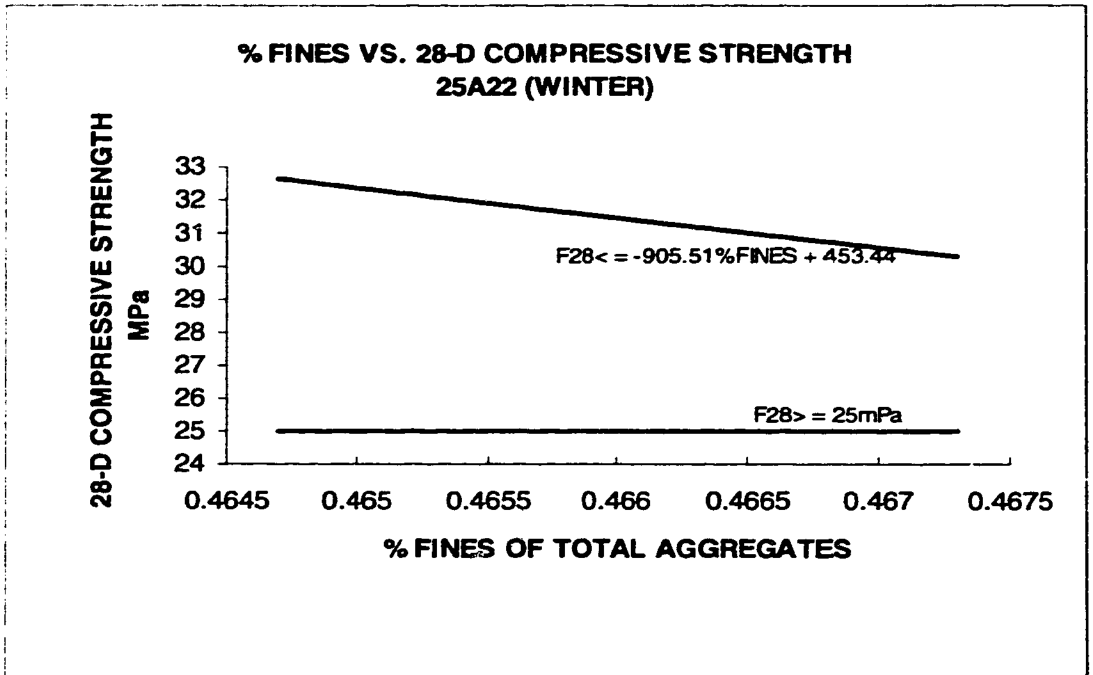
Mix No	Slump (mm)	Air Content (%)	Temperature	7-d Compressive Strength Mpa	28-d Compressive Strength Mpa
1	70	1.4	21	20.9	30.3
2	70	1.2	24	20.9	312
3	60	1.4	23	20.2	30.9
4	60	1.8	25	21.2	31.9
5	60	2.0	24	18.8	26.2
6	80	2.0	22	19.5	28.9
7	70	1.8	22	22.3	33.2
8	90	1.8	22	20.9	29.8
9	80	1.8	19	19.9	28.6
10	70	1.8	19	22.4	32.0
11	80	1.8	22	21.1	29.7

TABLE A-2 QUALITY CONTROL TEST RESULTS

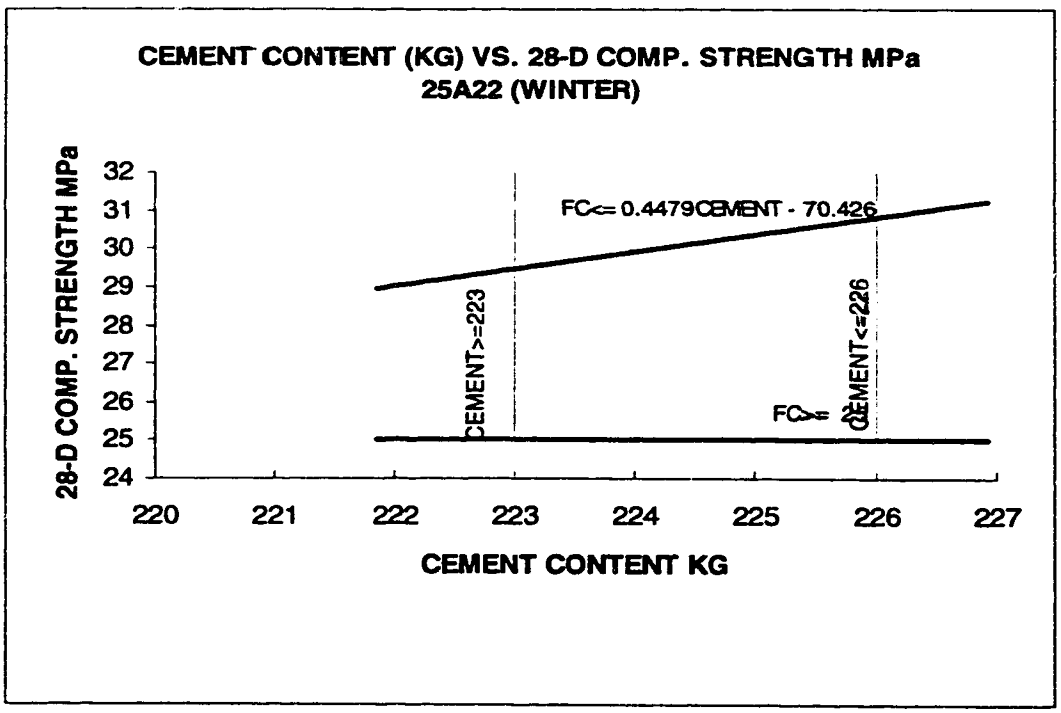
APPENDIX B GRAPHICAL REPRESENTATIONS OF ALL CONTINUOUS VARIABLES RELATIONSHIPS



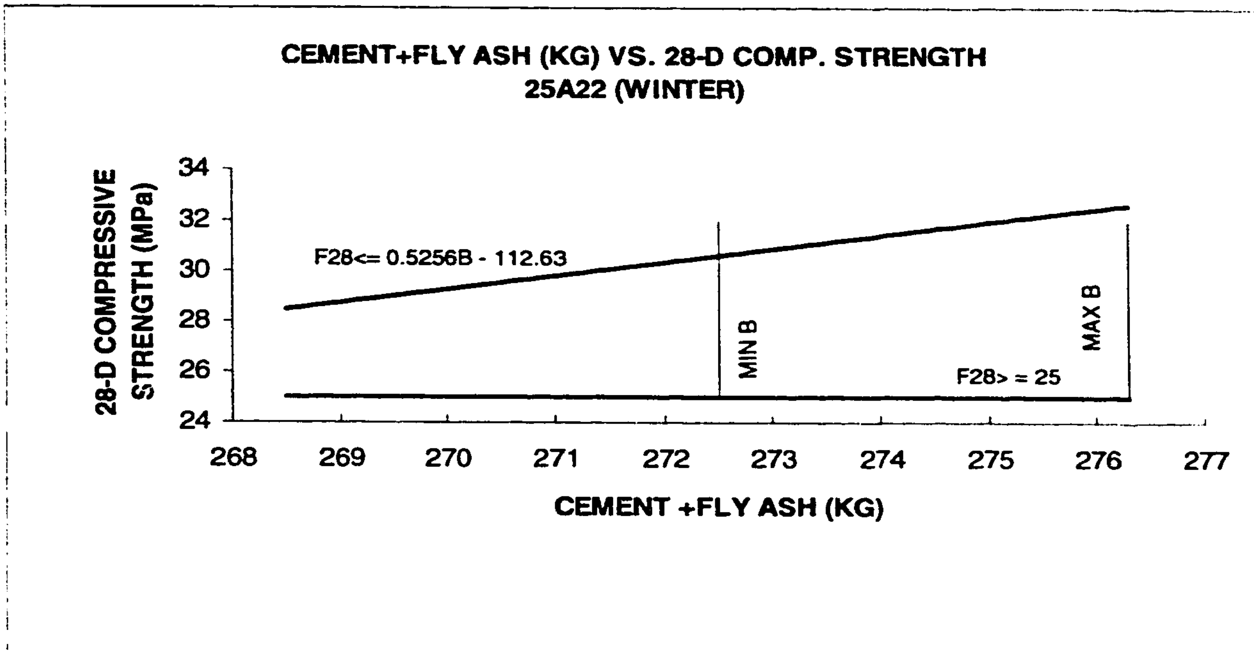


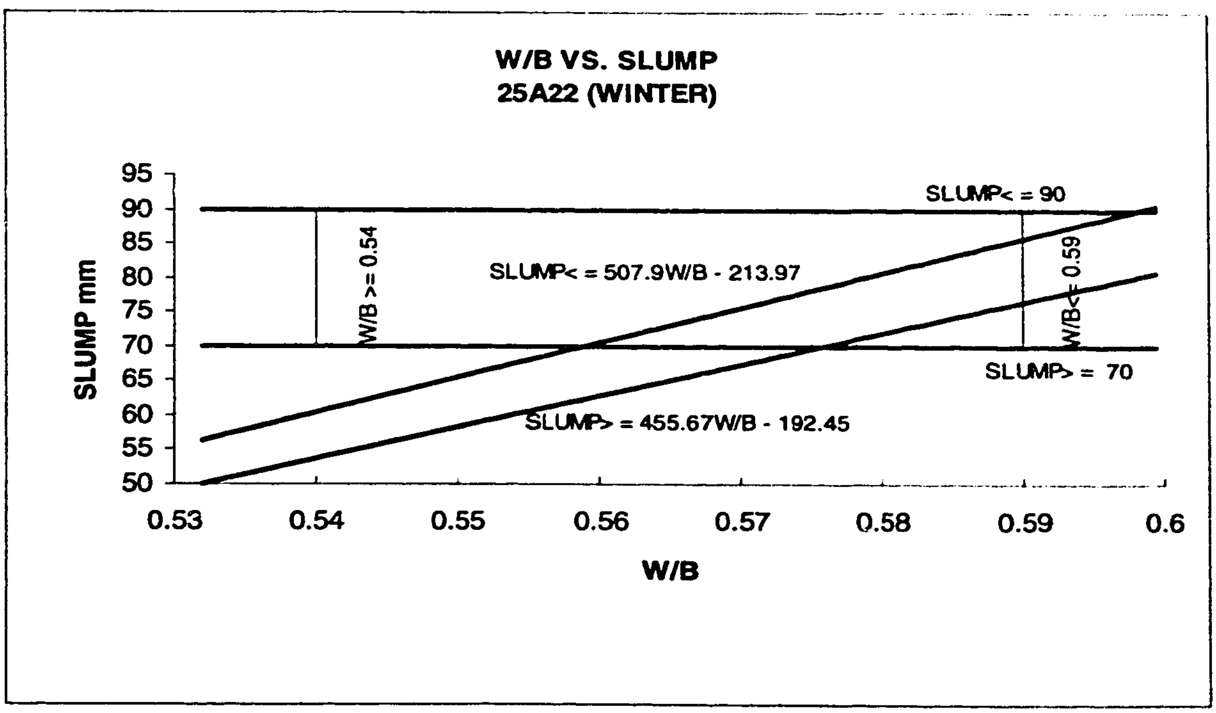


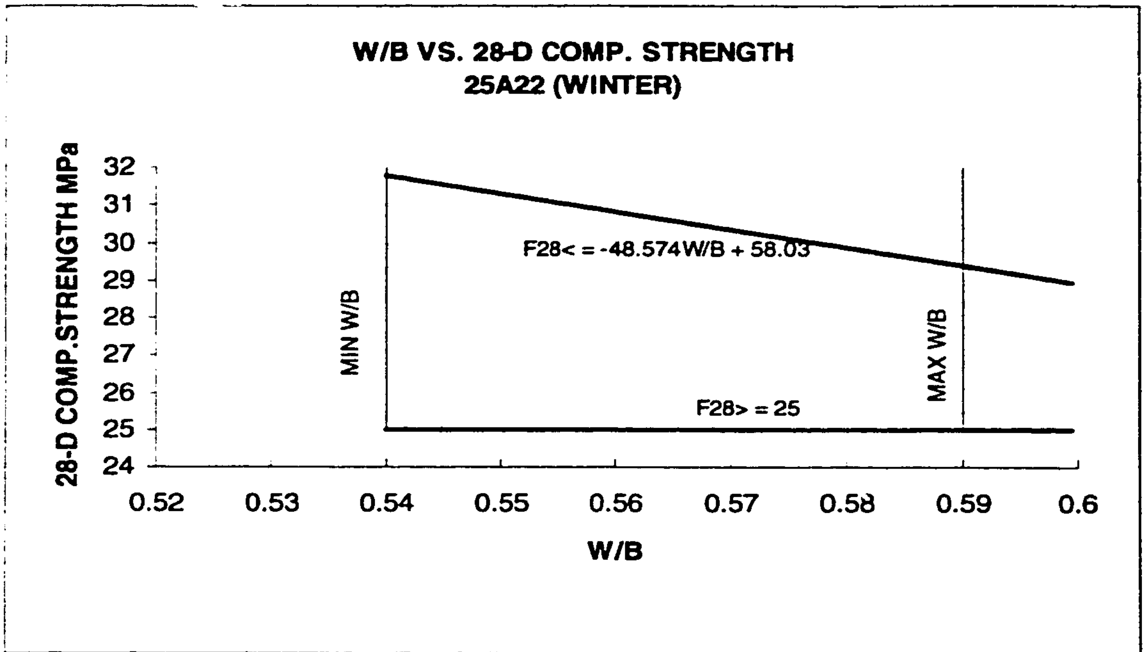
% FINES VS. 28-D COMPRESSIVE STRENGTH
25A22 (WINTER)
28-D COMPRESSIVE STRENGTH MPa
33
32
31
30
29
28
27
26
25
24
F28< = -905.51%FINES + 453.44
F28> = 25mPa
0.4645
0.465
0.4655
0.466
0.4665
0.467
0.4675
% FINES OF TOTAL AGGREGATES



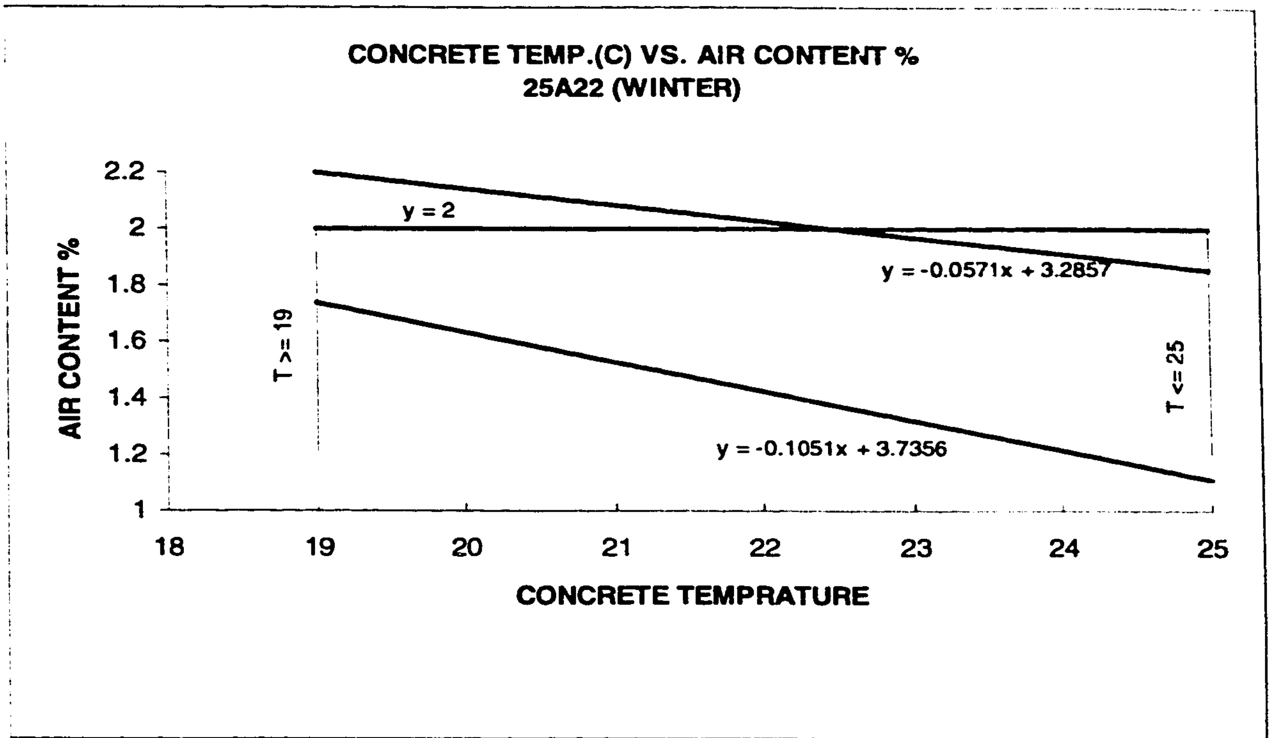
CEMENT CONTENT (KG) VS. 28-D COMP. STRENGTH MPa
25A22 (WINTER)
28-D COMP. STRENGTH MPa
32
31
30
29
28
27
26
25
24
FC<= 0.4479CEMENT - 70.426
CEMENT>=223
CEMENT<=226
220
221
222
223
224
225
226
227
CEMENT CONTENT KG

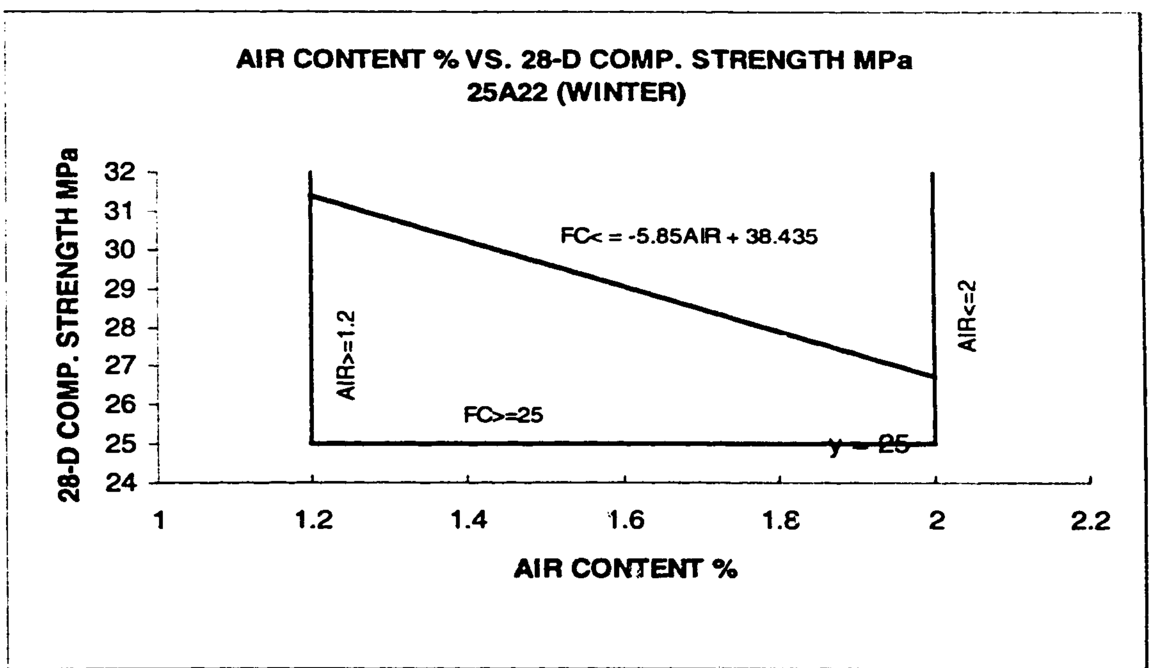

CEMENT+FLY ASH (KG) VS. 28-D COMP. STRENGTH
25A22 (WINTER)
28-D COMPRESSIVE STRENGTH (MPa)
34
32
30
28
26
24
F28<= 0.5256B - 112.63
MIN B
MAX B
F28> = 25
268
269
270
271
272
273
274
275
276
277
CEMENT +FLY ASH (KG)

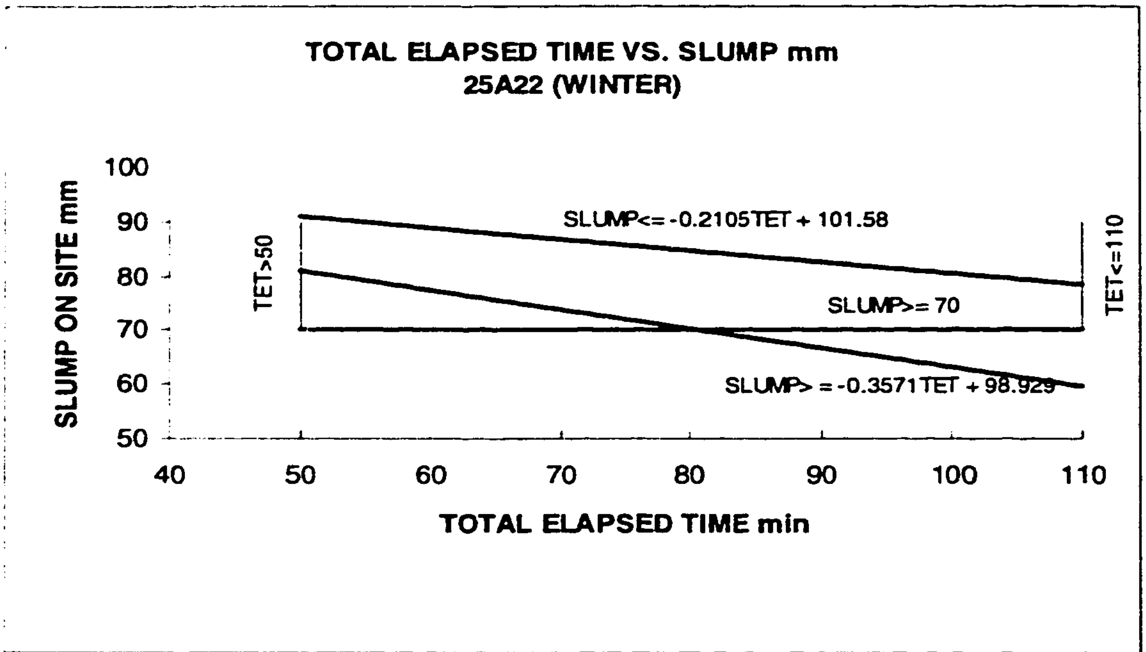

W/B VS. SLUMP
25A22 (WINTER)
SLUMP mm
95
90
85
80
75
70
65
60
55
50
SLUMP< = 90
W/B >= 0.54
SLUMP< = 507.9W/B - 213.97
W/B<= 0.59
SLUMP> = 70
SLUMP> = 455.67W/B - 192.45
0.53
0.54
0.55
0.56
0.57
0.58
0.59
0.6
W/B

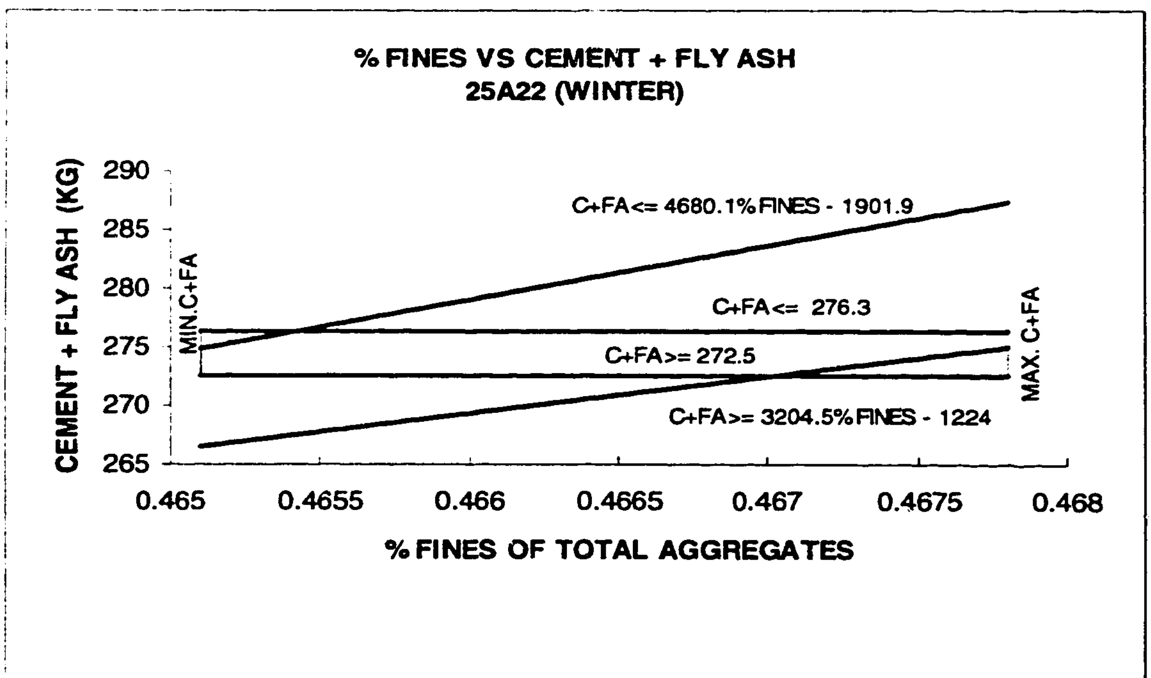


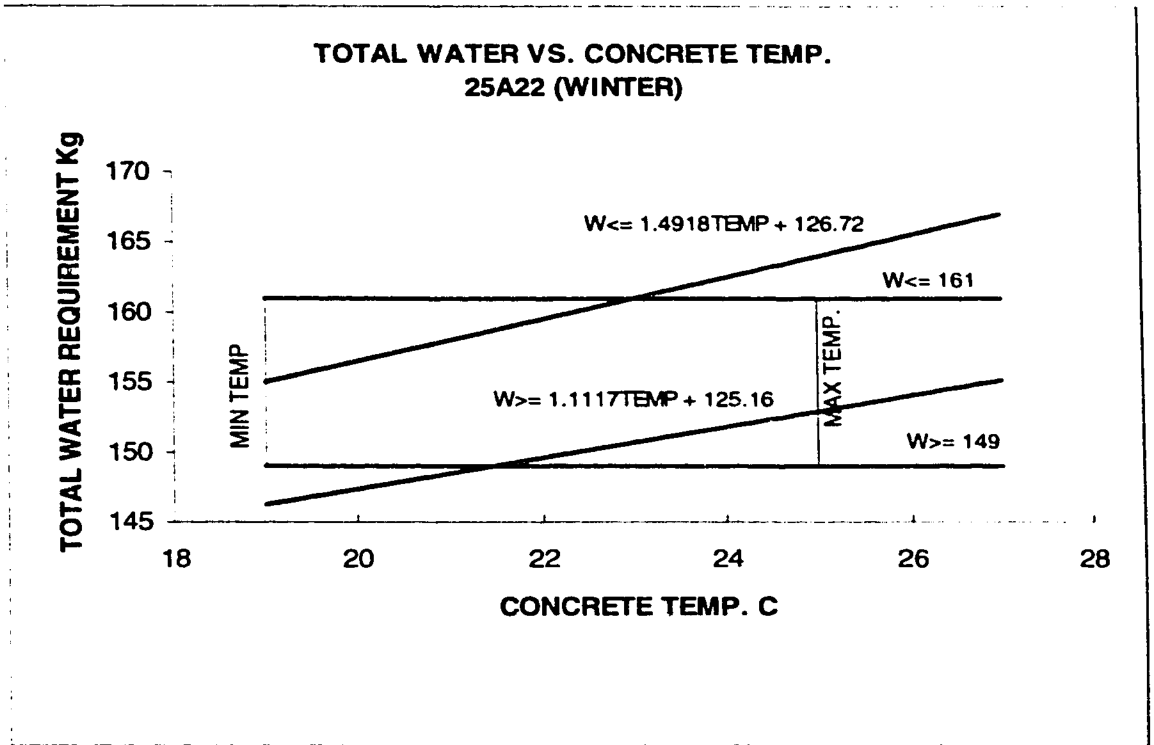
W/B VS. 28-D COMP. STRENGTH
25A22 (WINTER)
28-D COMP.STRENGTH MPa
32
31
30
29
28
27
26
25
24
0.52
0.53
0.54
0.55
0.56
0.57
0.58
0.59
0.6
W/B
MIN W/B
MAX W/B
F28< = -48.574W/B + 58.03
F28> = 25

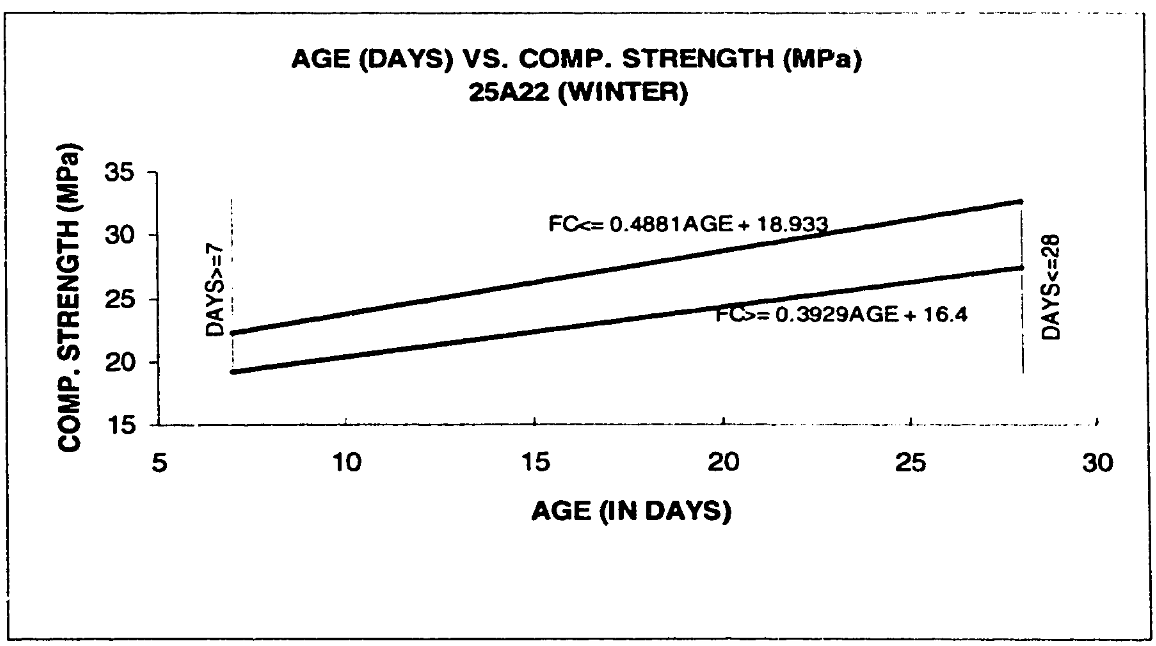

CONCRETE TEMP.(C) VS. AIR CONTENT %
25A22 (WINTER)
AIR CONTENT %
2.2
2
1.8
1.6
1.4
1.2
1
18
19
20
21
22
23
24
25
CONCRETE TEMPRATURE
y = 2
y = -0.0571x + 3.2857
y = -0.1051x + 3.7356
T >= 19
T <= 25

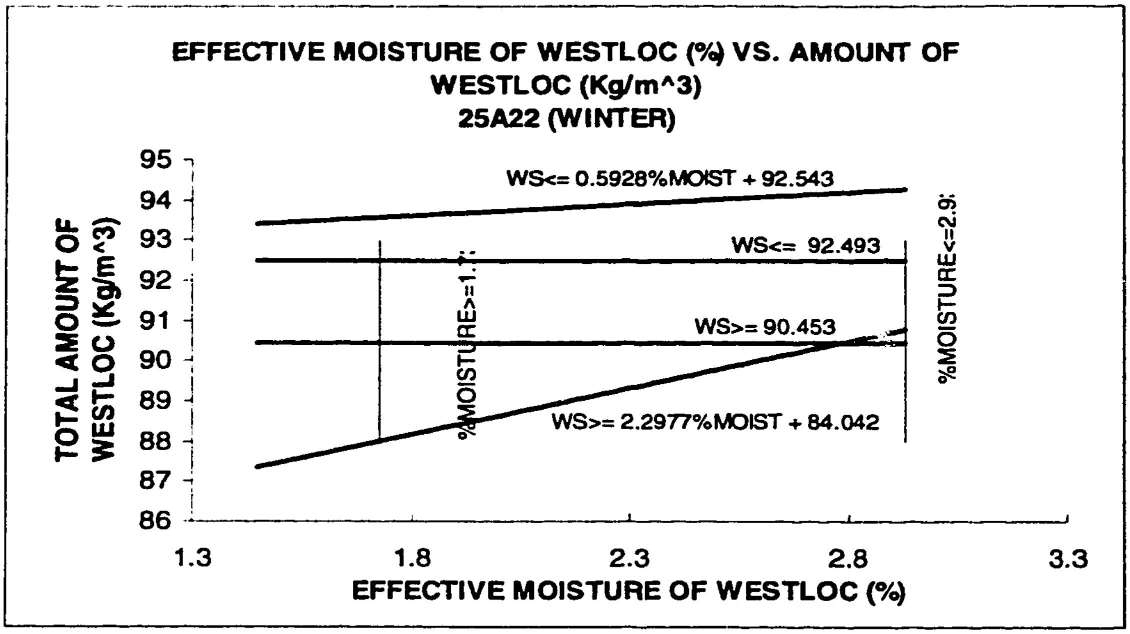

AIR CONTENT % VS. 28-D COMP. STRENGTH MPa
25A22 (WINTER)
28-D COMP. STRENGTH MPa
32
31
30
29
28
27
26
25
24
1
1.2
1.4
1.6
1.8
2
2.2
AIR CONTENT %
FC< = -5.85AIR + 38.435
AIR>=1.2
AIR<=2
FC>=25
y = 25

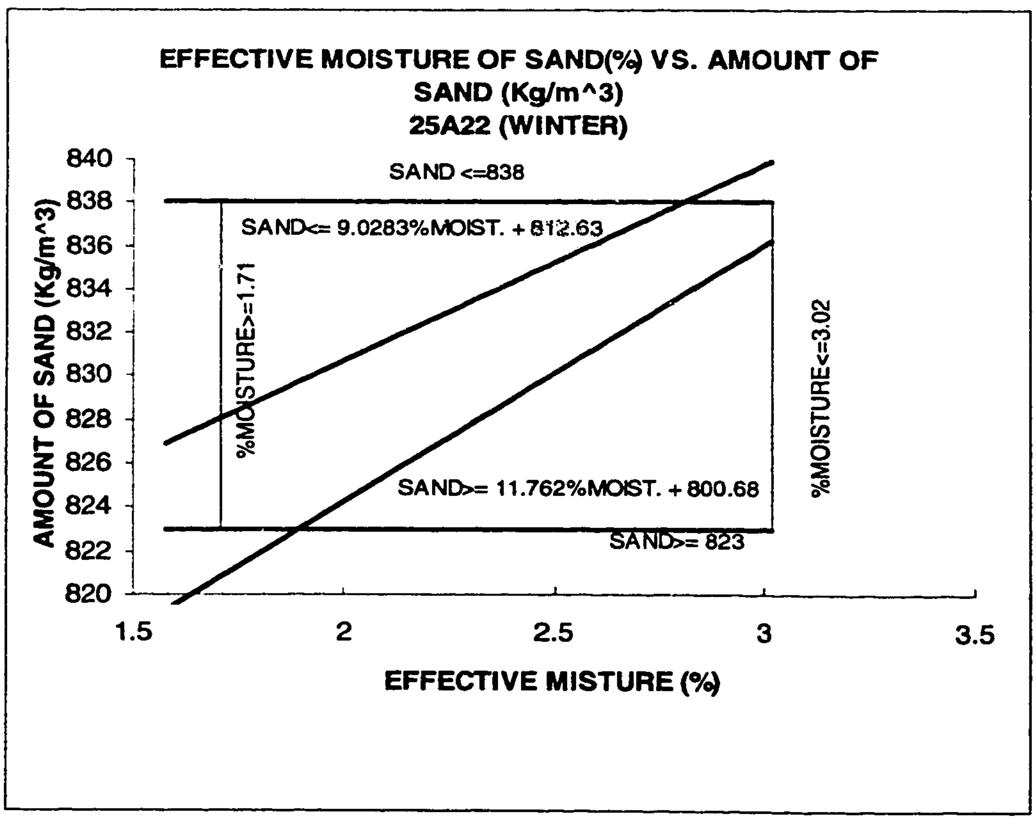

TOTAL ELAPSED TIME VS. SLUMP mm
25A22 (WINTER)
SLUMP ON SITE mm
100
90
80
70
60
50
40
50
60
70
80
90
100
110
TOTAL ELAPSED TIME min
SLUMP<= -0.2105TET + 101.58
SLUMP>= 70
SLUMP> = -0.3571TET + 98.929
TET>50
TET<=110

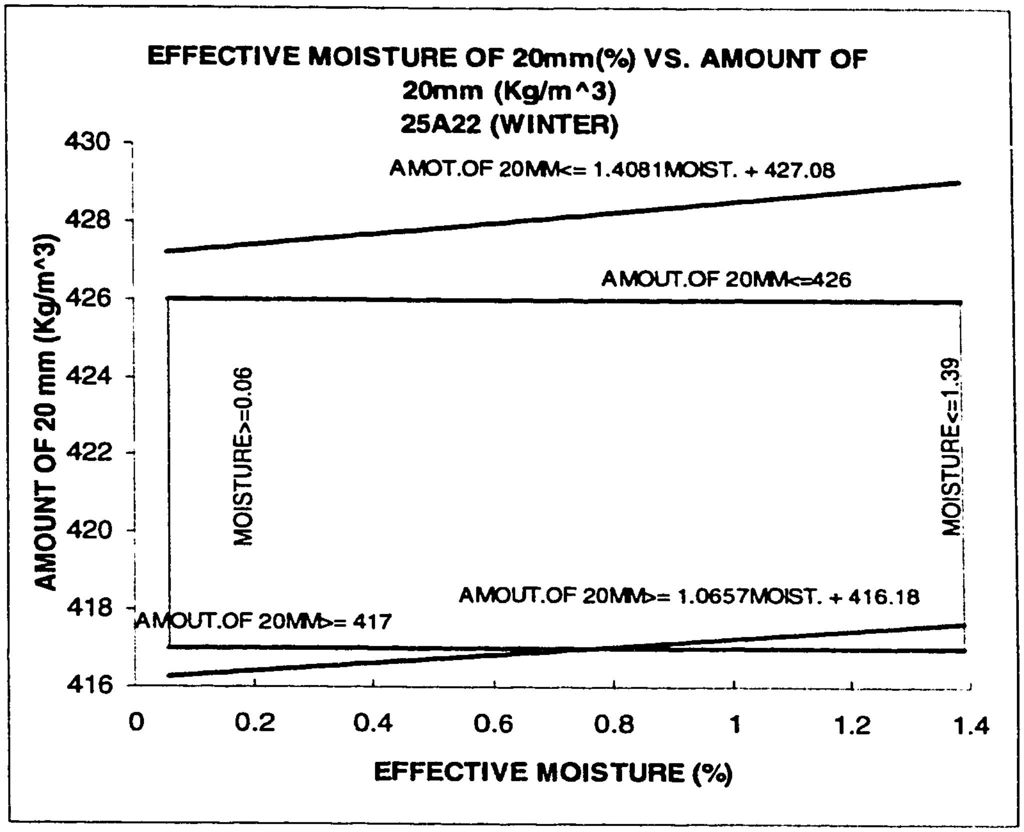

% FINES VS CEMENT + FLY ASH
25A22 (WINTER)
CEMENT + FLY ASH (KG)
290
285
280
275
270
265
0.465
0.4655
0.466
0.4665
0.467
0.4675
0.468
% FINES OF TOTAL AGGREGATES
C+FA<= 4680.1%FINES - 1901.9
C+FA<= 276.3
C+FA>= 272.5
C+FA>= 3204.5%FINES - 1224
MIN.C+FA
MAX. C+FA


TOTAL WATER VS. CONCRETE TEMP.
25A22 (WINTER)
TOTAL WATER REQUIREMENT Kg
170
165
160
155
150
145
18
20
22
24
26
28
CONCRETE TEMP. C
W<= 1.4918TEMP + 126.72
W<= 161
W>= 1.1117TEMP + 125.16
W>= 149
MIN TEMP
MAX TEMP.

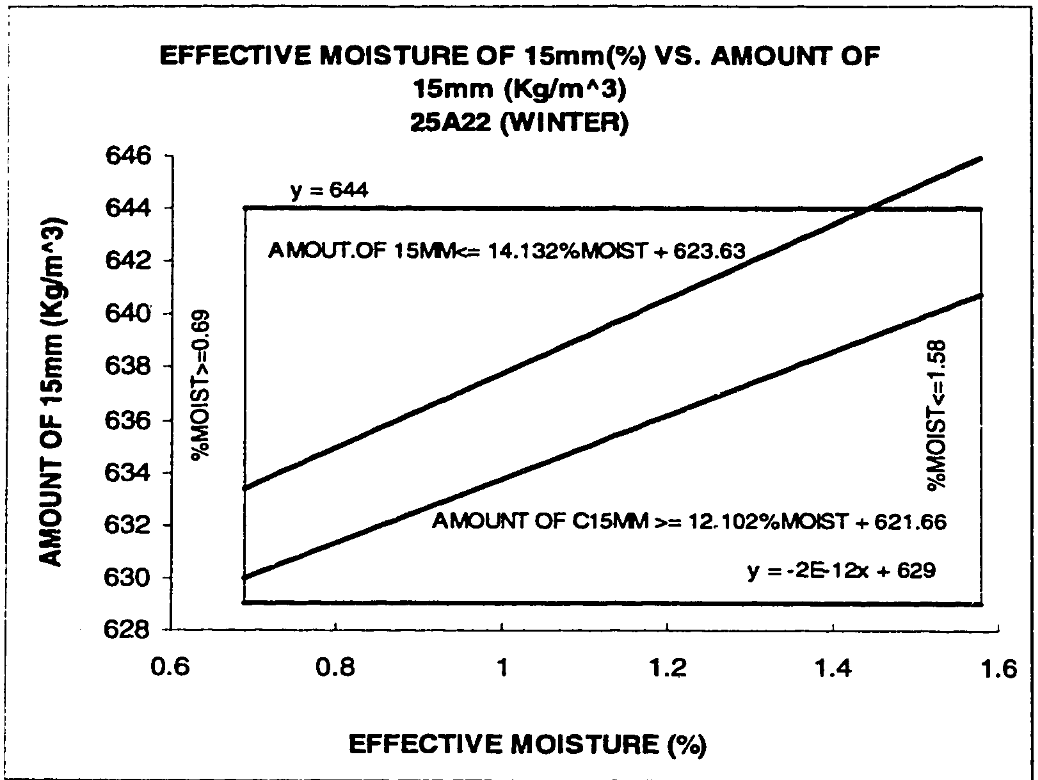

AGE (DAYS) VS. COMP. STRENGTH (MPa)
25A22 (WINTER)
COMP. STRENGTH (MPa)
35
30
25
20
15
5
10
15
20
25
30
AGE (IN DAYS)
FC<= 0.4881AGE + 18.933
FC>= 0.3929AGE + 16.4
DAYS>=7
DAYS<=28


EFFECTIVE MOISTURE OF WESTLOC (%) VS. AMOUNT OF WESTLOC (Kg/m^3)
25A22 (WINTER)
TOTAL AMOUNT OF WESTLOC (Kg/m^3)
95
94
93
92
91
90
89
88
87
86
WS<= 0.5928%MOIST + 92.543
WS<= 92.493
WS>= 90.453
WS>= 2.2977%MOIST + 84.042
%MOISTURE>=1.7
%MOISTURE<=2.9
1.3
1.8
2.3
2.8
3.3
EFFECTIVE MOISTURE OF WESTLOC (%)

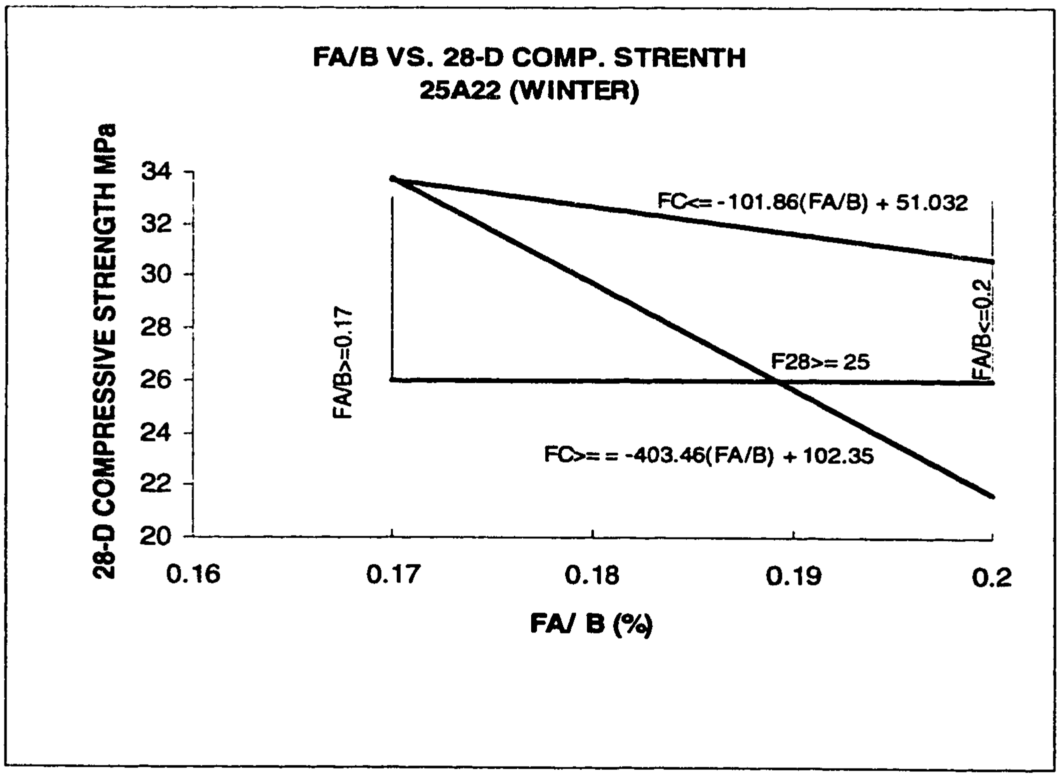

EFFECTIVE MOISTURE OF SAND(%) VS. AMOUNT OF SAND (Kg/m^3)
25A22 (WINTER)
AMOUNT OF SAND (Kg/m^3)
840
838
836
834
832
830
828
826
824
822
820
SAND <=838
SAND<= 9.0283%MOIST. + 812.63
%MOISTURE>=1.71
%MOISTURE<=3.02
SAND>= 11.762%MOIST. + 800.68
SAND>= 823
1.5
2
2.5
3
3.5
EFFECTIVE MISTURE (%)



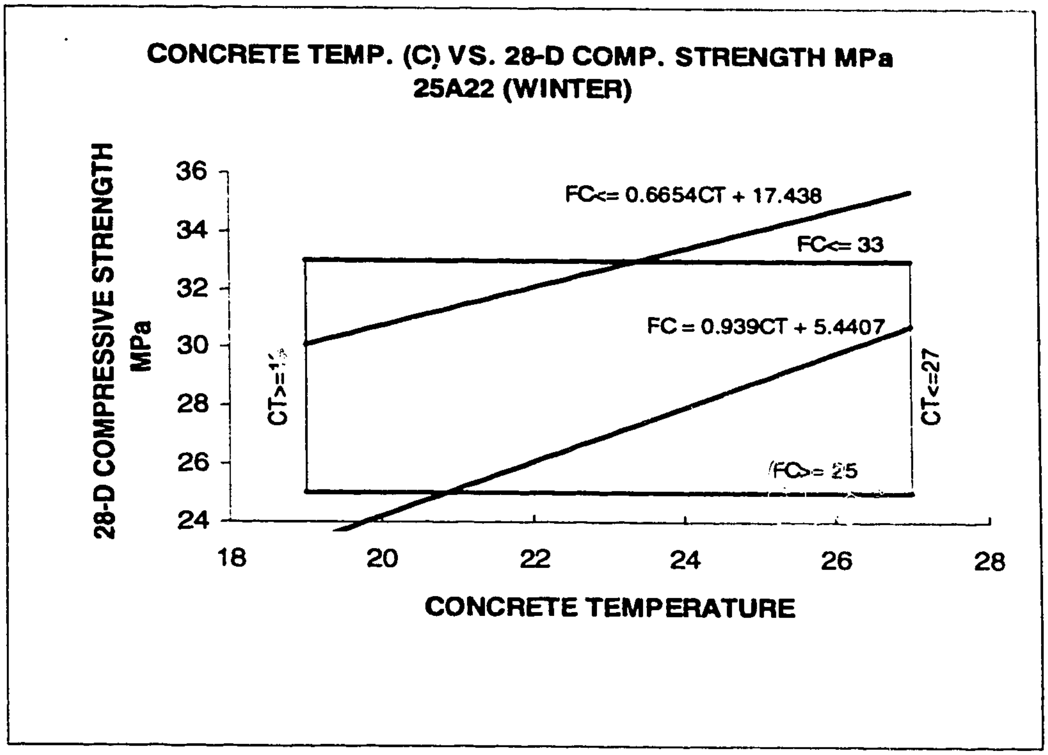
EFFECTIVE MOISTURE OF 20mm(%) VS. AMOUNT OF 20mm (Kg/m^3)
25A22 (WINTER)
AMOT.OF 20MM<= 1.4081MOIST. + 427.08
AMOUT.OF 20MM<=426
MOISTURE>=0.06
MOISTURE<=1.39
AMOUT.OF 20MM>= 1.0657MOIST. + 416.18
AMOUT.OF 20MM>= 417
AMOUNT OF 20 mm (Kg/m^3)
EFFECTIVE MOISTURE (%)
430
428
426
424
422
420
418
416
0
0.2
0.4
0.6
0.8
1
1.2
1.4

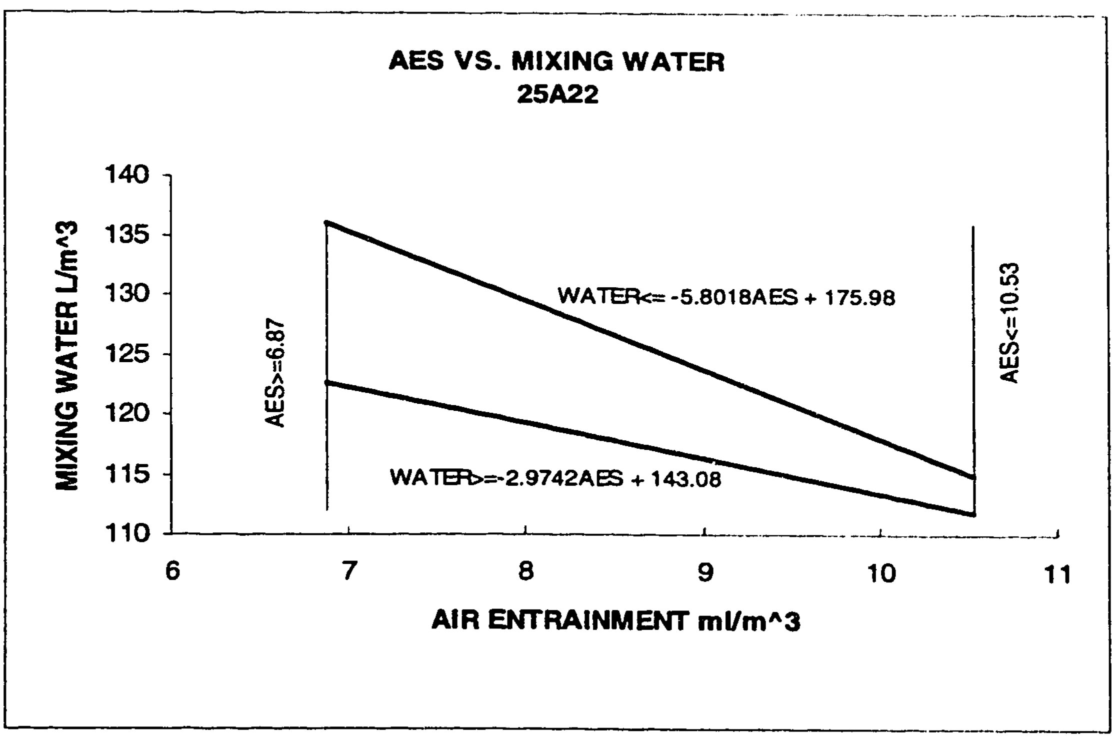


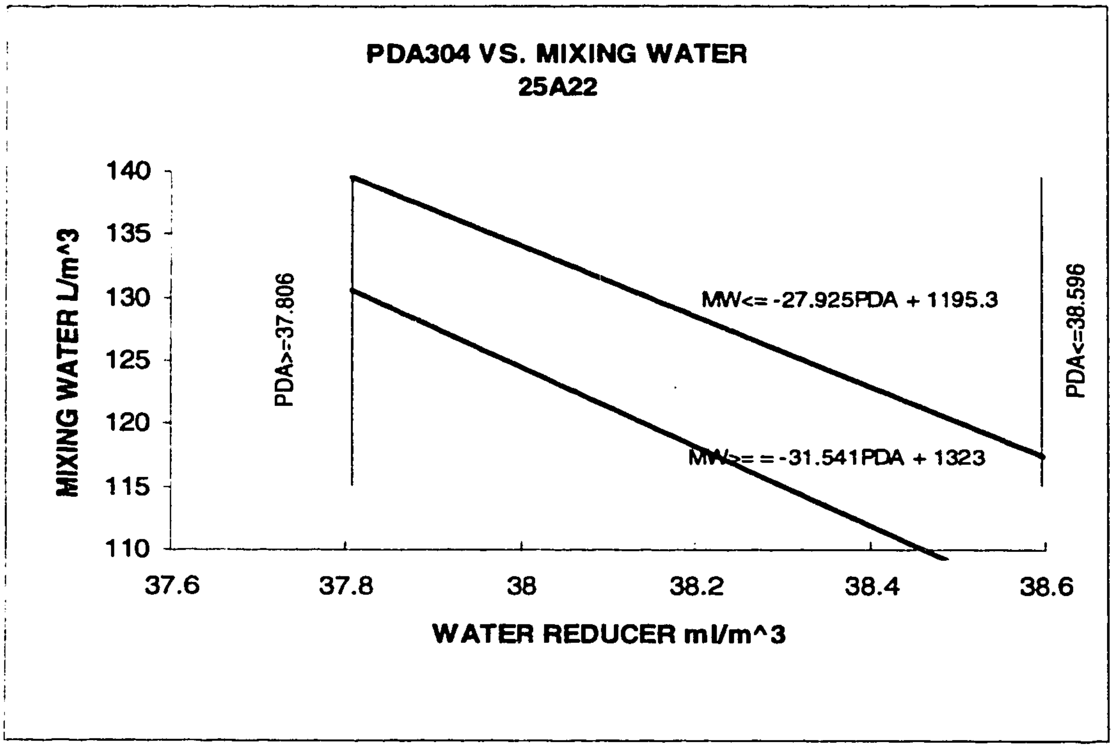
EFFECTIVE MOISTURE OF 15mm(%) VS. AMOUNT OF 15mm (Kg/m^3)
25A22 (WINTER)
y = 644
AMOUT.OF 15MM<= 14.132%MOIST + 623.63
%MOIST>=0.69
%MOIST<=1.58
AMOUNT OF C15MM >= 12.102%MOIST + 621.66
y = -2E-12x + 629
AMOUNT OF 15mm (Kg/m^3)
EFFECTIVE MOISTURE (%)
646
644
642
640
638
636
634
632
630
628
0.6
0.8
1
1.2
1.4
1.6



FA/B VS. 28-D COMP. STRENTH
25A22 (WINTER)
FC<= -101.86(FA/B) + 51.032
FA/B>=0.17
FA/B<=0.2
F28>= 25
FC>= = -403.46(FA/B) + 102.35
28-D COMPRESSIVE STRENGTH MPa
FA/ B (%)
34
32
30
28
26
24
22
20
0.16
0.17
0.18
0.19
0.2


CONCRETE TEMP. (C) VS. 28-D COMP. STRENGTH MPa
25A22 (WINTER)
28-D COMPRESSIVE STRENGTH MPa
36
34
32
30
28
26
24
18
20
22
24
26
28
CONCRETE TEMPERATURE
FC<= 0.6654CT + 17.438
FC<= 33
FC = 0.939CT + 5.4407
FC>= 25
CT<=27


AES VS. MIXING WATER
25A22
MIXING WATER L/m^3
140
135
130
125
120
115
110
6
7
8
9
10
11
AIR ENTRAINMENT ml/m^3
WATER<= -5.8018AES + 175.98
WATER>=-2.9742AES + 143.08
AES>=6.87
AES<=10.53



PDA304 VS. MIXING WATER
25A22
MIXING WATER L/m^3
140
135
130
125
120
115
110
37.6
37.8
38
38.2
38.4
38.6
WATER REDUCER ml/m^3
PDA>=37.806
PDA<=38.596
MW<= -27.925PDA + 1195.3
MW>= = -31.541PDA + 1323

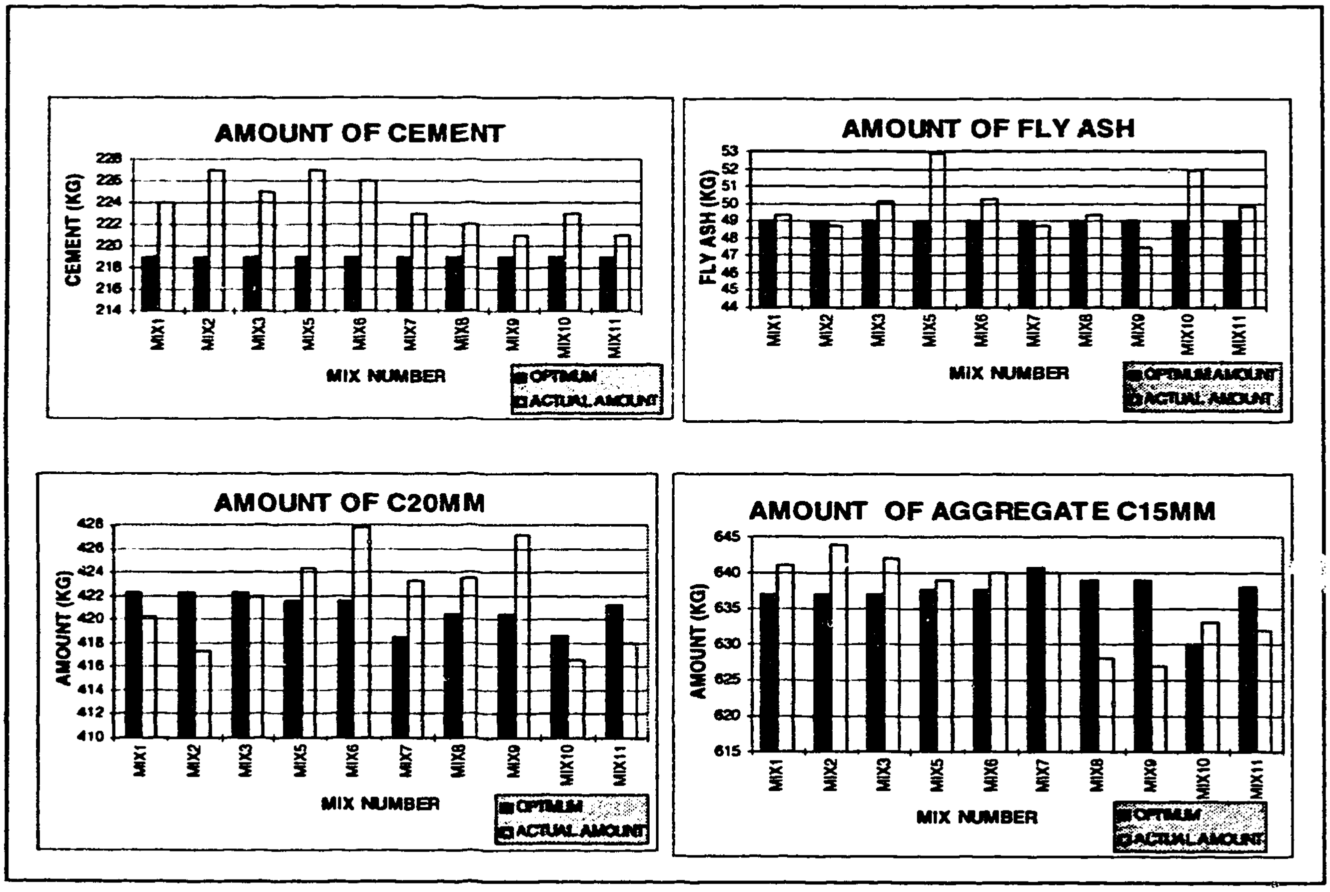
APPENDIX C : LINEAR PROGRAMMING MODEL FOR THE MIX DESIGN PROBLEM

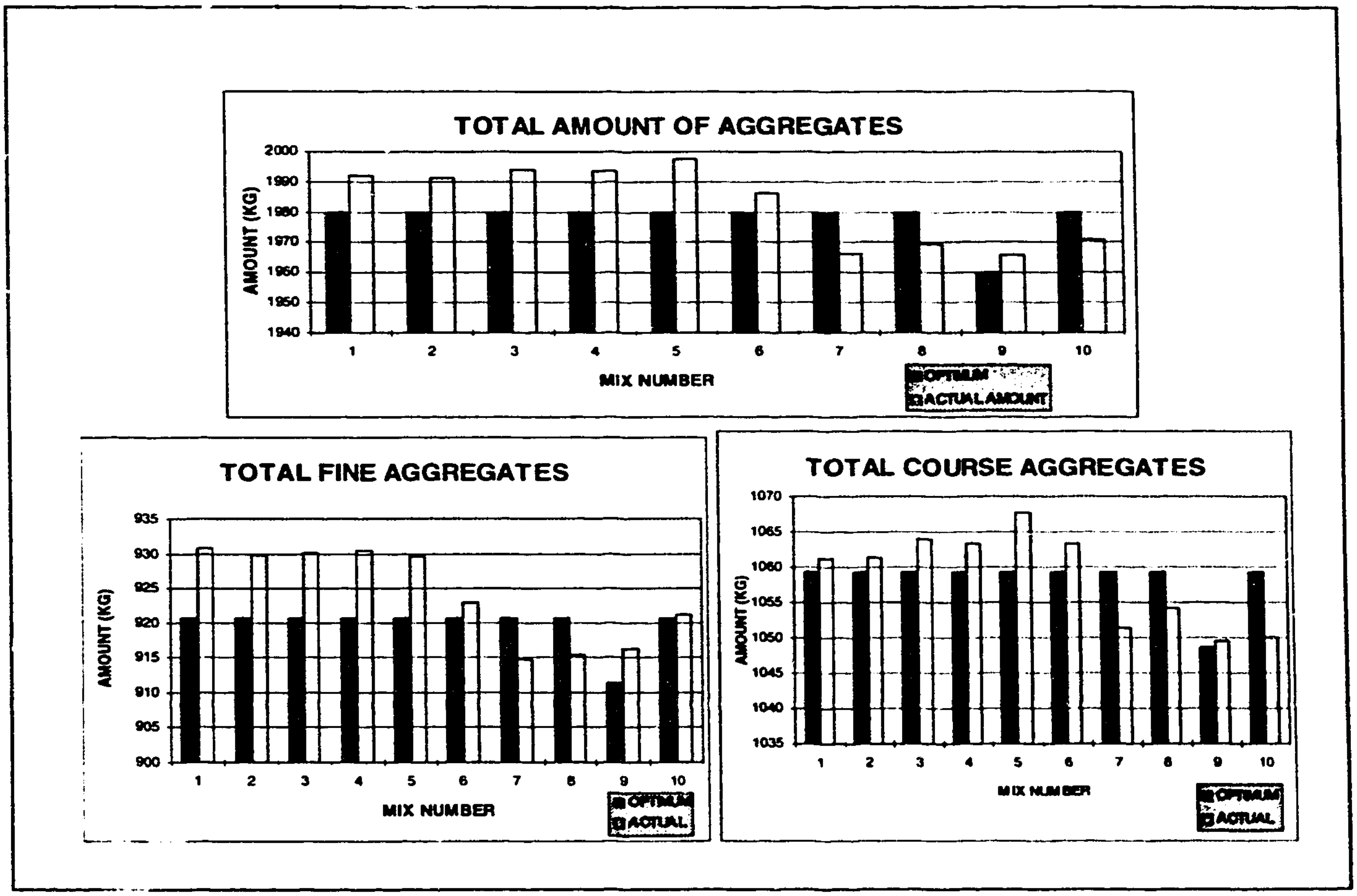
```
MIN COST
S.T.
COST-.12CEM-.0469FA-.01195C20MM-.01205C15MM-.0093CCLS-.0115WELC-.002MW-
.088PDA-0.20AES=0
TAG-1960.000Y1-1970.000Y2-1980.000Y3-1990.000Y4-2000.000Y5=0
TFAG- 891.8x11- 901.6x12- 911.4x13- 921.2x14- 931x15-
 896.35x21- 906.2x22- 916.05x23- 925.9x24- 935.75x25-
 900.9x31- 910.8x32- 920.7x33- 930.6x34- 940.5x35-
 905.45x41- 915.4x42- 925.35x43- 935.3x44- 945.25x45-
 910x51- 920x52- 930x53- 940x54- 950x55=0
x11+x12+x13+x14+x15-Y1=0
x21+x22+x23+x24+x25-Y2=0
x31+x32+x33+x34+x35-Y3=0
x41+x42+x43+x44+x45-Y4=0
x51+x52+x53+x54+x55-Y5=0
x11+x21+x31+x41+x51-X1=0
x12+x22+x32+x42+x52-X2=0
x13+x23+x33+x43+x53-X3=0
x14+x24+x34+x44+x54-X4=0
x15+x25+x35+x45+x55-X5=0
x1+x2+x3+x4+x5=1.0
TFAG-CCLS-WELC=0
.0270CCLS+.0970WELC>=0
-.0230CCLS+.0470WELC<=0
.1400CCLS+.2340WELC>=0
-.0600CCLS+.0340WELC<=0
.1110CCLS+.3070WELC>=0
-.2890CCLS-.0930WELC<=0
-.0560CCLS+.3690WELC>=0
-.4560CCLS-.0310WELC<=0
.0610CCLS+.3130WELC>=0
-.1890CCLS+.0630WELC<=0
.0420CCLS+.0900WELC>=0
-.0380CCLS+.0100WELC<=0
TAG-TFAG-TCAG=0
TCAG-C15MM-C20MM=0
.0000C15MM+.0510C20MM>=0
-.1000C15MM-.0490C20MM<=0
-.1920C15MM+.5180C20MM>=0
-.4170C15MM+.2930C20MM<=0
-.0570C15MM+.5620C20MM>=0
-.4070C15MM+.2120C20MM<=0
.0920C15MM+.0910C20MM>=0
.0080C15MM+.0090C20MM>=0
.0420C15MM+.0500C20MM>=0
.0080C15MM+.0000C20MM>=0
MF1=3.02
CCLS-9.028MF1<=812.627
MF2=1.86
WELC-2.298MF2>=84.042
```

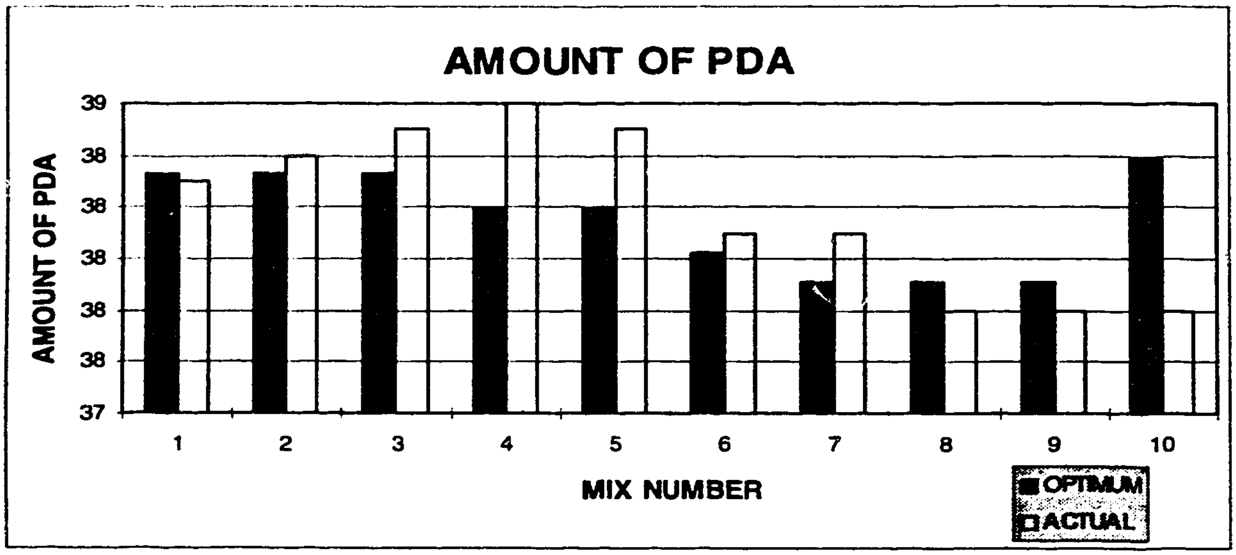
```
MC1=1.27
C15MM-14.132MC1<=623.626
C15MM-12.103MC1>=621.656
MC2=1.39
C20MM-1.066MC2>=416.181
.455X1+.4600X2+.4650X3+.4700X4+.4750X5-PF=0
4680.076PF-CEM-FA>=1901.946
3204.486PF-CEM-FA<=1223.986
.526CEM+.526FA-F28>=112.635
F28>=25
.448CEM-F28>=70.426
CEM<=226
905.505PF+F28<=453.435
MW+.0302CCLS+.0186WELC+.0127C15MM+.0139C20MM-TW=0
WBR-.5522R11-.5481R12-.5441R13-.5401R14-.5362R15-
 .5597R21-.5556R22-.5515R23-.5474R24-.5435R25-
 .5672R31-.563R32-.5588R33-.5547R34-.5507R35-
 .5746R41-.5704R42-.5662R43-.562R44-.558R45-
 .5821R51-.5778R52-.5735R53-.5693R54-.5652R55-
 .5896R61-.5852R62-.5809R63-.5766R64-.5725R65-
 .597R71-.5926R72-.5882R73-.5839R74-.5797R75-
 .6045R81-.6R82-.5956R83-.5912R84-.587R85=0
R11+R12+R13+R14+R15-R1=0
R21+R22+R23+R24+R25-R2=0
R31+R32+R33+R34+R35-R3=0
R41+R42+R43+R44+R45-R4=0
R51+R52+R53+R54+R55-R5=0
R61+R62+R63+R64+R65-R6=0
R71+R72+R73+R74+R75-R7=0
R81+R82+R83+R84+R85-R8=0
R11+R21+R31+R41+R51+R61+R71+R81-S1=0
R12+R22+R32+R42+R52+R62+R72+R82-S2=0
R13+R23+R33+R43+R53+R63+R73+R83-S3=0
R14+R24+R34+R44+R54+R64+R74+R84-S4=0
R15+R25+R35+R45+R55+R65+R75+R85-S5=0
R1+R2+R3+R4+R5+R6+R7+R8=1.0
148.00R1+150.00R2+152.00R3+154.00R4+156.00R5+158.00R6+160.00R7+162.00R8-TW=0
268.00S1+270.00S2+272.00S3+274.00S4+276.00S5-B=0
CEM+FA-B=0
F28+48.574WBR<=58.03
507.901WBR-SLUMP>=213.973
455.668WBR-SLUMP<=192.454
SLUMP<=90
SLUMP>=70
SLUMP+7798.2PF<=3716.4
SLUMP+5261.4PF>=2516.7
81.119PF-AIR>=35.915
40.816PF-AIR<=17.723
AIR<=2
FC-.488DAYS<=18.933
FC-.393DAYS>=16.4
DAYS=28
FC-F28=0
AIR+.057CT<=3.286
```

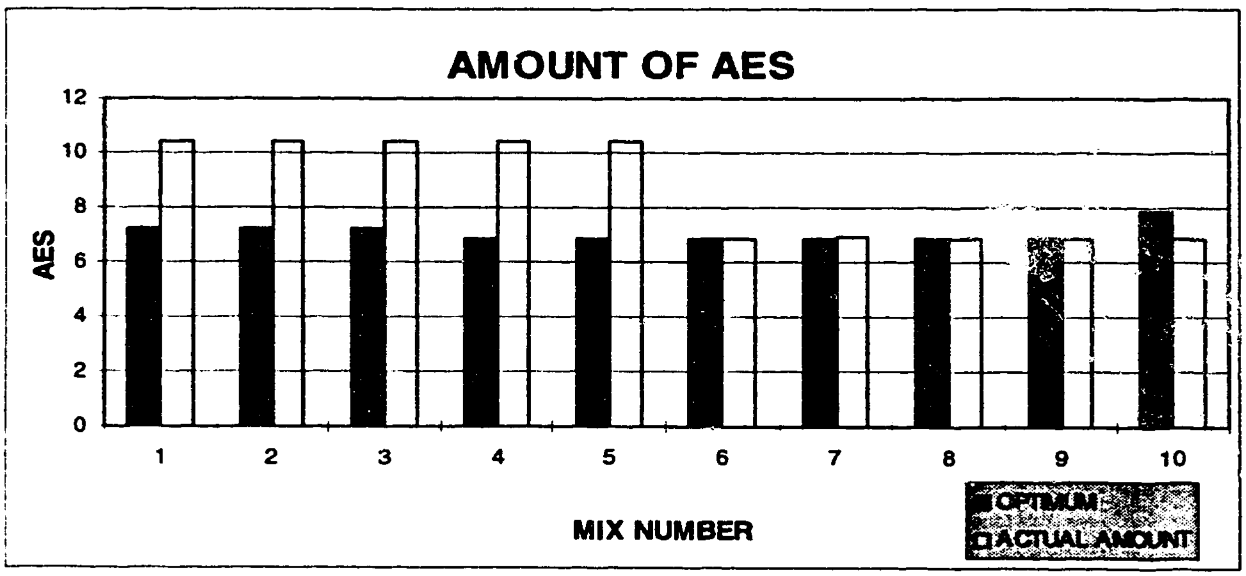
AIR+.105CT>=3.736
CT<=25
CT>=19
TW-1.492CT<=126.717
TW-1.112CT>=125.165
F28+5.85AIR<=38.435
SLUMP+.211TET<=101.579
SLUMP+.357TET>=98.929
TET=55
FABR-.1754Q11-.1741Q12-.1728Q13-.1715Q14-.1703Q15-
.1828Q21-.1815Q22-.1801Q23-.1788Q24-.1775Q25-
.1903Q31-.1889Q32-.1875Q33-.1861Q34-.1848Q35-
.1978Q41-.1963Q42-.1949Q43-.1934Q44-.192Q45=0
Q11+Q12+Q13+Q14+Q15-P1=0
Q21+Q22+Q23+Q24+Q25-P2=0
Q31+Q32+Q33+Q34+Q35-P3=0
Q41+Q42+Q43+Q44+Q45-P4=0
Q11+Q21+Q31+Q41-S1=0
Q12+Q22+Q32+Q42-S2=0
Q13+Q23+Q33+Q43-S3=0
Q14+Q24+Q34+Q44-S4=0
Q15+Q25+Q35+Q45-S5=0
47P1+49P2+51P3+53P4-FA=0
F28+403.462FABR<=102.349
FABR>=0.17
FABR<=0.20
F28-.665CT<=17.439
F28-.939CT>=5.441
TAG+CEM+FA+MW-UW=0
UW>=2200
UW<=2400
MW+5.8AES<=175.98
MW+2.974AES>=143.1
AES>=6.874
AES<=10.53
MW+27.925PDA<=1195.25
MW+31.341PDA>=1322.981
PDA<=38.596
PDA >=37.806

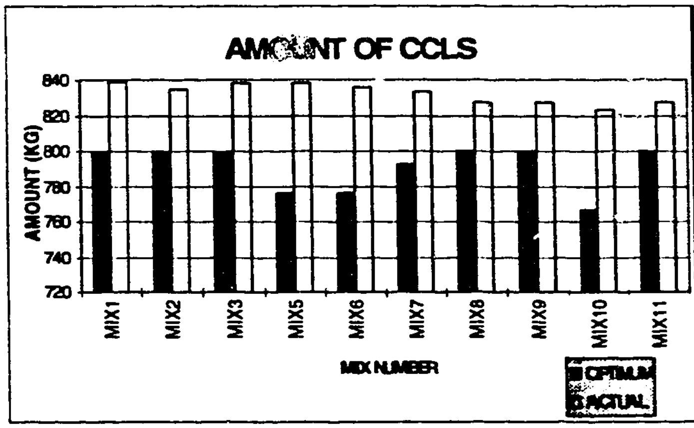
APPENDIX D OPTIMUM AND ACTUAL INGREDIENTS AMOUNTS

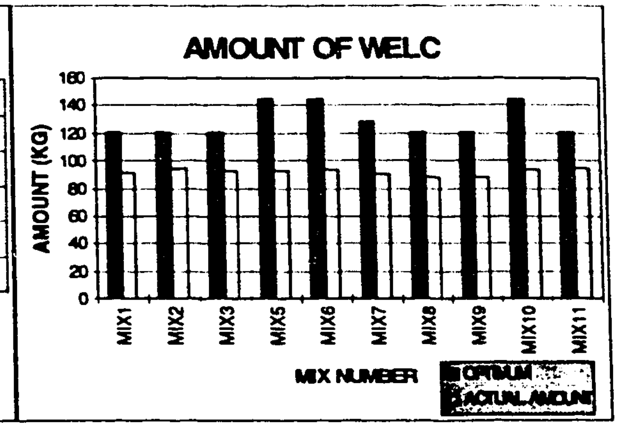


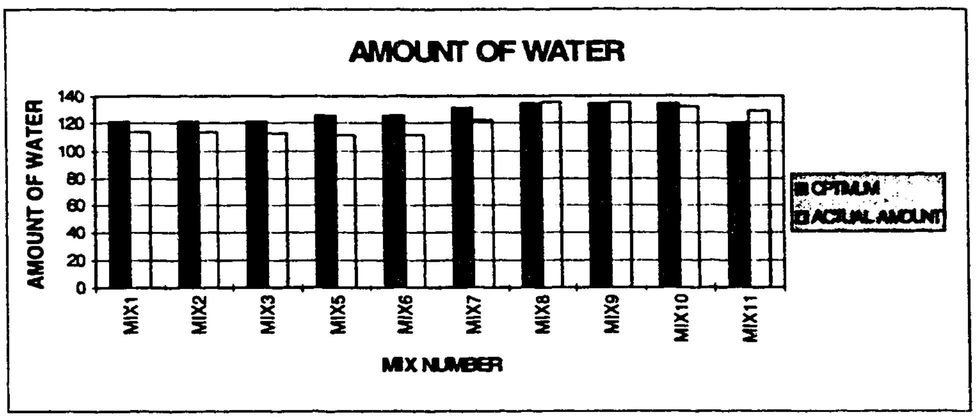

TOTAL AMOUNT OF AGGREGATES
AMOUNT (KG)
MIX NUMBER
OPTIMUM
ACTUAL AMOUNT
TOTAL FINE AGGREGATES
AMOUNT (KG)
MIX NUMBER
OPTIMUM
ACTUAL
TOTAL COURSE AGGREGATES
AMOUNT (KG)
MIX NUMBER
OPTIMUM
ACTUAL


AMOUNT OF PDA
AMOUNT OF PDA
39
38
38
38
38
38
38
37
1
2
3
4
5
6
7
8
9
10
MIX NUMBER
OPTIMUM
ACTUAL


AMOUNT OF AES
AES
12
10
8
6
4
2
0
1
2
3
4
5
6
7
8
9
10
MIX NUMBER
OPTIMUM
ACTUAL AMOUNT


AMOUNT OF CCLS
AMOUNT (KG)
840
820
800
780
760
740
720
MIX1
MIX2
MIX3
MIX5
MIX6
MIX7
MIX8
MIX9
MIX10
MIX11
MIX NUMBER
OPTIMUM
ACTUAL


AMOUNT OF WELC
AMOUNT (KG)
160
140
120
100
80
60
40
20
0
MIX1
MIX2
MIX3
MIX5
MIX6
MIX7
MIX8
MIX9
MIX10
MIX11
MIX NUMBER
OPTIMUM
ACTUAL AMOUNT


AMOUNT OF WATER
AMOUNT OF WATER
140
120
100
80
60
40
20
0
MIX1
MIX2
MIX3
MIX5
MIX6
MIX7
MIX8
MIX9
MIX10
MIX11
MIX NUMBER
OPTIMUM
ACTUAL AMOUNT

CHAPTER 4: EQUIPMENT ALLOCATION

INTRODUCTION

Equipment management includes areas such as maintenance, replacement, performance and utilization. The main concern in this research is the utilization of the equipment.

For medium and large construction companies involved in underground and road works, the main resource used is heavy equipment (dozers, scrapers, backhoes). Usually companies have an equipment division which keeps all the information related to the equipment (price, purchase date, depreciation, maintenance, performance etc.) Besides the equipment division, companies may have their operations division assign the equipment required for projects. When the company is large and have several districts, each one is assigned its own equipment to perform the projects. Generally speaking companies have three possibilities to get equipment to carry out the projects:

1. Using its own equipment
2. Renting equipment
3. Subcontracting the job

When projects are awarded allocation decisions should be made not only to satisfy demand requirements but also to ensure that these decisions are the best for the company. Different allocation options should be analyzed and in doing so management is supposed to use the following criteria before making any decisions:

- Duration of projects
- Resource requirements
- Volume

- Estimated cost
    1. F.O.G. (fuel, oil and gas)
    2. Repair
    3. Use (Depreciation)
- Actual costs
- Revenue : for every project
- Owner considerations (some owners do not like the company to subcontract any part of the job)
- Subcontracting (company sometimes may subcontract part of the job)
- Transportation costs

Companies usually use cost control systems to evaluate the project's performance so if there is any deficiency, corrective actions can be made. In this way, as the project is carried out, it is possible to predict the cost and the duration of it. This suggests that if there is any change in the duration or cost estimates the allocation system should be able to see how these changes could affect the current allocation.

The initial situation faced by the company will eventually change since new projects can arrive at any time or projects under execution are finished. In any case, the equipment allocation decision adopted at any time should be the best one for the interests of the company. Essentially companies want to optimize the use of their assets and also their employees' time.

The objective of this work is to develop a computerized implementation for a linear programming formulation of the equipment allocation problem. The implementation should have the following attributes:

- Integration and self containment in such a way that the user does not have to use more than one system to solve an equipment allocation problem.
- Flexible to allow implementation for different organizations.

To achieve this objective the following was done:

1. A linear optimization formulation proposed by Pritsker (1967) was studied and developed further.
2. A database was created to facilitate the manipulation of the equipment information.
3. A program was developed in Visual Basic.
4. A case study was used to validate the model.

EQUIPMENT ALLOCATION

A decision to allocate and/or rent equipment according to contracts won and under execution has to be made. An evaluation of different possibilities has to be done in order to make the best decision for the company.

Every time a new event arises the whole situation should be evaluated so a new allocation or reallocation will take place according to the circumstances. This means that whatever system or way of solving the problem is used it has to be dynamic. In this context dynamic means that the system or solution process will respond to changes as they occur. Events that can change or affect the allocation of the equipment at any time given an initial allocation are :

- A new project has arrived
- A current project has finished
- Actual activities duration are different than those estimated
- Actual equipment costs are different than those estimated

Commonly the allocation of equipment in the construction industry relies on the experience of the operations manager. He/she will assign the equipment according to the circumstances. Figure 4-1 shows a general conceptual model for the scheduling and allocation process.

This process begins with the awarding of one or more projects. Then each project is broken down into small units called work packages which generally speaking represent the tasks to be done. Based on productivity rates, the duration of every task is calculated. Finally an initial or basic schedule can be established based on the activity precedence relationships and on the activity duration. Traditionally the schedule is modeled by a network (CPM, PERT, Precedence or a bar chart). The schedule obtained by following this process assumes that the resources available are enough to cover the demand. Unfortunately this is not the case in real life. The schedule for each project has to be adjusted according to the availability of resources.

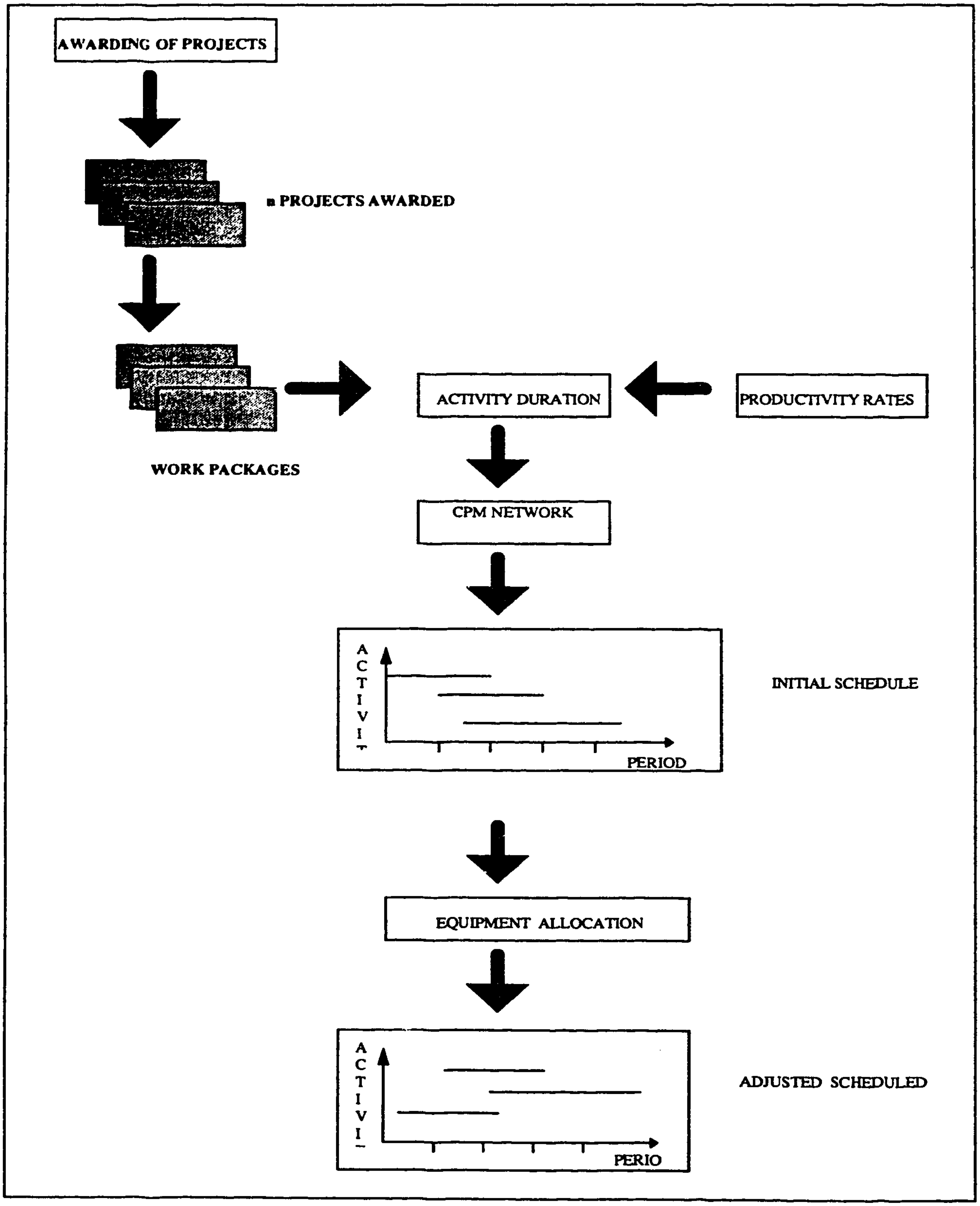


FIGURE 4-1 CONCEPTUAL SCHEDULING MODEL

However before following the model some questions will arise. For example when calculating an activity duration the scheduler will have to decide between a deterministic approach or a probabilistic approach. With this in mind and to define the scope of this work some initial conditions must be established. In general the following are the initial conditions for the equipment allocation problem:

- The company knows how many projects have to be carried out and when. The company has estimated the amount of work to be done, its duration and its cost. Activities duration are deterministic.
- Equipment requirements are known.
- Equipment availability is known.
- There are only two options available to get the equipment required:

1. Use of the company's equipment
2. Renting equipment

- The cost of using the company's equipment, renting equipment are also known.
- Equipment transportation costs are known.

SOLUTION PROCESS

Figure 4-2 shows the logic process used in solving the dynamic allocation problem. This process includes a mathematical model as a key element in the allocation problem. Basically the mathematical model analyzes all the possible allocation schemes. Based on this analysis the best alternative will be selected by the model. The measurement of performance used by the model to select an allocation scheme is given by an objective function. Basically this process has two phases:

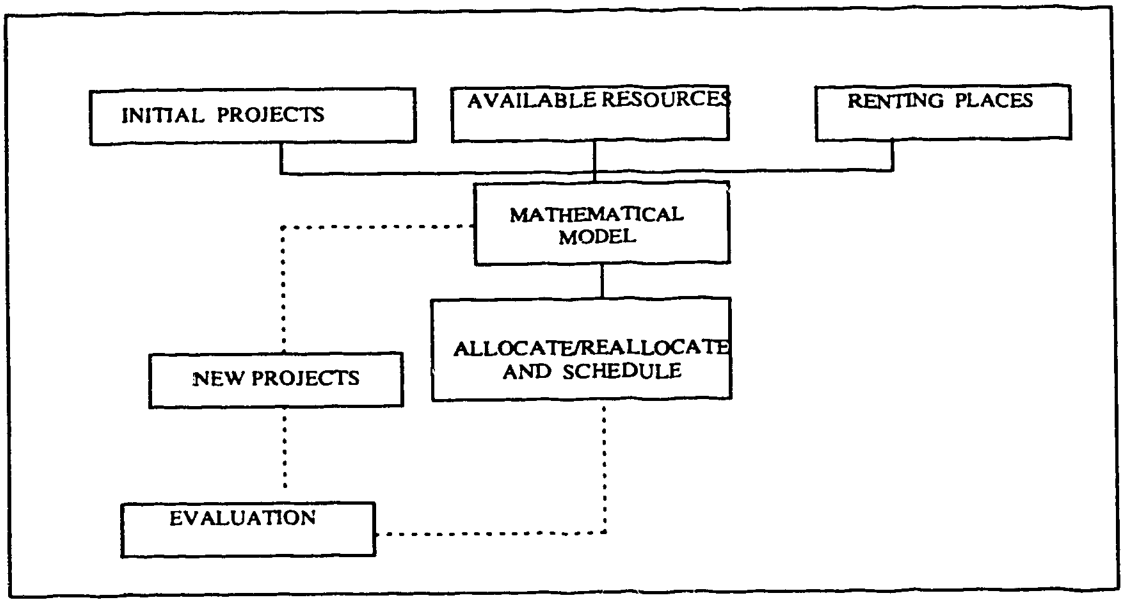


FIGURE 4-2 DYNAMIC PROBLEM

Phase I Initial Allocation

There is an initial situation in which the number of projects, the available resources and the renting places are known. The mathematical model will evaluate the initial situation and it will decide what the best allocation scheme is according to the objective function.

Phase II Subsequent Allocation

After the initial allocation has taken place new events could change or affect the current allocation. New projects may arrive or old projects may be finished. At this point an evaluation and allocation/reallocation may take place. When a new project arrives, the new allocation will have to consider that point in time as the initial situation so the model will be used in the same way it was used in phase I.

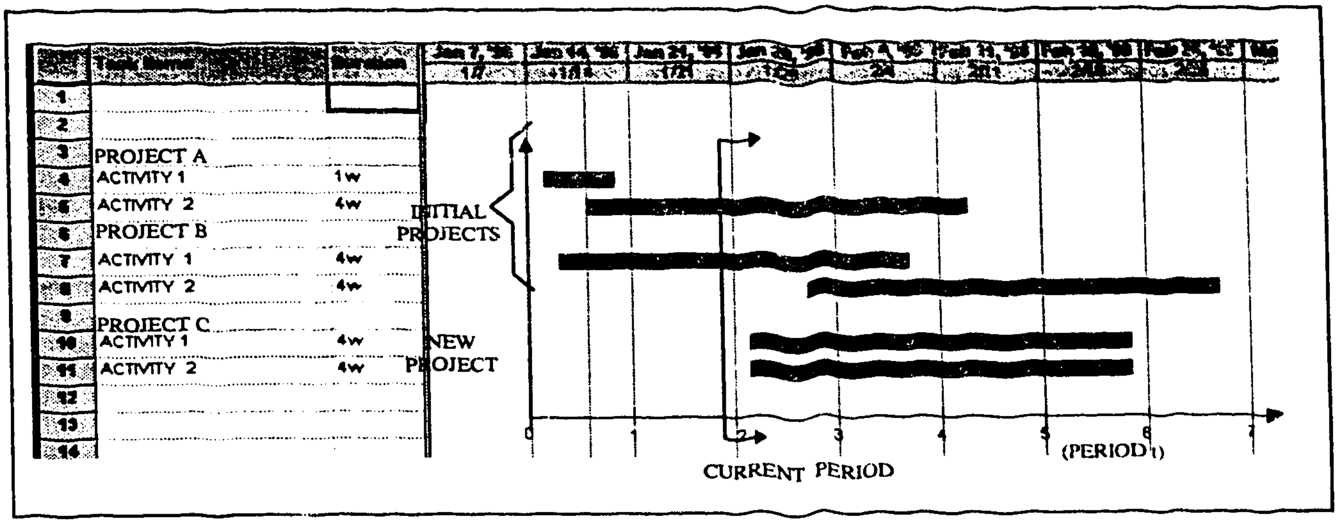


FIGURE 4-3 ARRIVAL OF A NEW PROJECT

Considering the situation depicted in Figure 4-3 in which the arrival of a new project is presented, there were two initial projects in period 0 (project A and project B) and an initial allocation was performed. The current period is period 2 and a new project arrives (project C) and projects A and B are still under execution.

At this point project A has only one activity left and project B has two activities to be completed. The model will consider that project A is composed of one activity and project B is composed of two activities. The duration of the first one is going to be the remaining amount of time to complete that activity.

There are two basic objectives when allocating or scheduling equipment. 1) complete the projects in the least possible amount of time with the available resources and 2)minimize rental of equipment.

MINIMIZING OVERALL PROJECTS DURATION

Pristker et al (1967) developed a mathematical model for multiproject scheduling with limited resources. The model is a (0/1) linear programming model used to schedule several projects, each with different activities and with different resource requirements. The main objective is to determine the best possible schedule in order to complete all projects with limited resources in the least amount of time.

The basic idea is to minimize the time required to accomplish all the projects subject to the following conditions:

- Limited amount of resources
- A determined precedence relationship between activities
- Project and job due dates

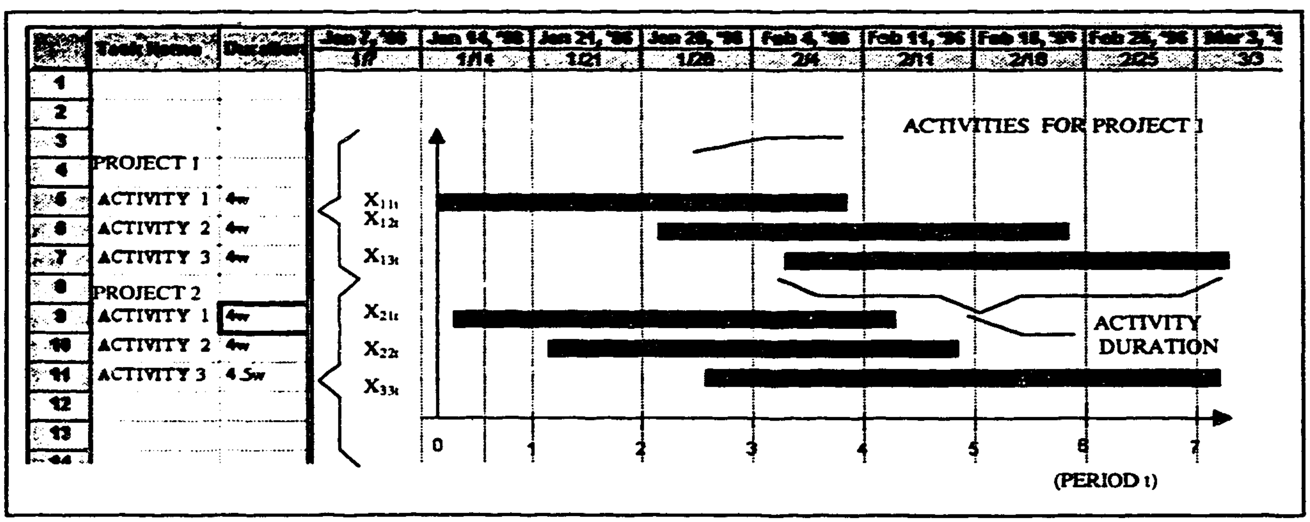


FIGURE 4-4 ELEMENTS OF PROJECTS

Figure 4-4 shows the elements considered in developing the model. Basically there is a determined number of projects under consideration, each with a specific number of activities requiring a given number of resources. There are also precedence relationships between activities which are assumed to be known.

The type of variables used to represent this situation are 0/1 variables which have the form X_{ijt} . An X_{ijt} variable is 1 if the activity j of project i is completed in period t; 0 otherwise. Due to the precedence relationships between activities it is not necessary to consider a variable X_{ijt} for all the periods. The model will minimize the time required to perform all the projects provided that resources, milestones, activities and project completion constraints are met.

Definitions

In developing the model the following is used to define various variables:

i= project number, i=1,2 ... I . I= number of projects

j=activity number, j=1,2..., N_i =number of activities in project i.

t=time period, t=1,2,...max G_i. G_i= absolute due date. Project i must be completed in or before period G_i.

g_i=desired due date.

e_i=earliest possible period by which project i could be completed.

a_{ij}= arrival period of job j, project i. Arrivals occur at the beginning of periods.

d_{ij}=number of periods required to perform job j of project i. It is assumed to know with certainty.

l_{ij}=the earliest possible period in which job j could be completed.

u_{ij}= the latest possible period in which job j could be completed.

k=resource or facility number, k=1,2,... K. K=number of different resource types.

r_{ijk}=amount of type k resource required on job j of project i.

R_{kt}=amount of type k resource available in period t.

X_{ijt}= a variable which is 1 if activity j of project i is completed in period t; 0 otherwise. Xijt is 0 for $t<l_{ij}$ and for $t>u_{ij}$.

X_{it}=a variable which is 1 in period t if all jobs of project i have been completed by period t. X_{it} is 0 for $t<e_i$ and 1 for $t>G_i$.

Objective Function

Activities should be scheduled in a way that some measure of performance is optimized. In this case the measure of performance is the time required to complete all the projects. The objective is to minimize the total throughput time for the projects. Throughput time is defined as the elapsed time between project arrival and project completion. Project completion occurs when all the activities of a project have been completed. Minimizing throughput time for a project is equivalent to maximizing the number of periods after the project is completed. The objective function can be written as

$$\text{Maximize } Z = \sum_{i=1}^{I}\sum_{t=ei}^{Gi} X_{it}$$

Constraints

Activity completion

Every activity must have only one completion period. This requirement can be written as

$$\sum_{t=lij}^{uij} X_{ijt} = 1 \quad (i=1,2,..,I;\ j=1,2,..,N_i)$$

Project completion

X_{it} variables are zero until all of its jobs have been completed. In other words, project i can not be completed by period t until $\sum_{q=l_{ij}}^{t-1} X_{ijt} = 1$ for all N_i activities of project i. This constraint can be written as

$$X_{it} \leq (1/\ N_i) \sum_{j=1}^{N_i} \sum_{q=l_{ij}}^{t-1} X_{ijq} \quad (I=1,2,\ldots,\ I);\ t= e_i,\ e_i+1..,G_i)$$

Sequencing relations

A sequencing relationship is required when an activity cannot be started until one or more other activities have been completed. If on project I , activity m must precede activity n, t_{in} and t_{im} are the completion period for these activities then

$$t_{im} + d_{in} \leq t_{in}$$

$$t_{im} = \sum_{t=l_{im}}^{u_{im}} tX_{imt} \text{ and } t_{in} = \sum_{t=l_{in}}^{u_{in}} tX_{int}$$

Therefore this requirement can be written as

$$\sum_{t=l_{im}}^{u_{im}} tX_{imt} + d_{in} \leq \sum_{t=l_{in}}^{u_{in}} tX_{int}$$

Resource constraints

Resources required by an activity are assumed in use until the activity ends. The r_{ijk} variable represents the number of units of resource type k required by activity j of project i. In any given period, the amount of resource k used on all jobs cannot exceed the amount of resource k available. A job is being processed in period t if the job is completed in period q where $t \leq q \leq t + d_{ij} - 1$. The resource constraint can be expressed as follows

$$\sum_{i=1}^{I}\sum_{j=1}^{N_i}\sum_{q=t}^{t+d_{ij}-1} r_{ijk}X_{ijq} \leq R_{kt} \qquad (t= \min a_{ij},\ldots, \max G_i;\ k= 1,2,\ldots K)$$

Once the model is solved a new and optimized schedule can be derived since the completion period for each activity is provided by the model and the activity duration is an input for the model. In essence the model will provide the schedule that has the least possible duration. Note that the implementation of some of these constraints requires recognizing predetermined values of Xijt. The only possible periods to finish any activity are between its earliest completion period and its latest completion period.

MINIMIZING EQUIPMENT RENTAL MODEL

For this model the main purpose is to minimize rental costs. It is assumed that the rental information is known. Basically the different possible places to rent equipment as well as the renting costs have to be available. Companies usually have access beforehand to the rental rates. The model will evaluate the situation according to the number of projects to perform, resource availability, and resource requirements.

Definitions

i= project number, i=1,2 ... I . I= number of projects

j=activity number, j=1,2..., N_i =number of activities in project i.

t=time period, t=1,2,...max G_i. G_i= absolute due date. Project i must be completed in or before period G_i.

g_i=desired due date.

e_i=earliest possible period by which project i could be completed.

a_{ij}= arrival period of job j, projeci i. Arrivals occur at the begining of periods.

d_{ij}=number of periods required to perform job j of project i. It is assumed to know with certainty.

l_{ij}=the earliest possible period in which job j could be completed.

u_{ij}= the latest possible period in which job j could be completed.

k=resource or facility number, k=1,2,... K. K=number of different resource types.

r_{ijk}=amount of type k resource required on job j of project i.

p=renting place number. p=1,2,... P; P=total number of places to rent equipment.

R_{kt}=amount of type k resource available in period t.

XR_{ijktp}= number of units of resource type k rented from renting place p on period t for activity j of project i.

XO_{ijk}=number of units owned of resource type k assigned to activity j of project i.

CR_{kp}= cost of renting resource type k from place p.

X_{ijt}= a variable which is 1 if activity j of project i is completed in period t; 0 otherwise. Xijt is 0 for $t<l_{ij}$ and for $t>u_{ij}$.

X_{it}=a variable which is 1 in period t if all jobs of project i have been completed by period t. X_{it} is 0 for $t<e_i$ and 1 for $t>G_i$.

Objective Function

The objective is to minimize the renting of equipment. The objective function can be written as

$$\text{Minimize } Z = \sum_{i=1}^{I}\sum_{j=1}^{Ni}\sum_{k=1}^{k}\sum_{t=ei}^{Gi}\sum_{p=1}^{P} XR_{ijktp} * CR_{pk}$$

Constraints

Resource requirements

In any given period the amount of resources assigned which are owned plus the amount of resources rented have to be equal to the resource requirements. An activity is being processed in period t if the activity is completed in period q where $t \leq q \leq t + d_{ij} - 1$. Therefore this requirement can be written as

$$\sum_{i=1}^{I}\sum_{j=1}^{Ni}\sum_{q=t}^{t+dij-1} r_{ijk}X_{ijq} - XO_{ijkt} - \sum_{p=1}^{P} XR_{ijktp} = 0 \quad (t=\min a_{ij},\ldots, \max G_i; k=1,2,\ldots,K)$$

Activity completion

Every activity must have only one completion period. This constraint can be written as

$$\sum_{t=lij}^{uij} X_{ijt} = 1 \quad (i=1,2,..,I; j=1,2,..,N_i)$$

Sequencing relations

A sequencing relationship is required when an activity cannot be started until one or more other jobs have been completed. If on project I , activity m must precede activity n, t_{in} and t_{im} are the completion period for these activities then

$$t_{im} + d_{in} \leq t_{in}$$

$t_{im} = \sum_{t=lim}^{uim} tX_{imt}$ and $t_{in} = \sum_{t=lin}^{uin} tX_{int}$ therefore this requirement can be written as

$$\sum_{t=lim}^{uim} tX_{imt} + d_{in} \leq \sum_{t=lin}^{uin} tX_{int}$$

Resource availability

At any period the amount of own resources assigned has to be less or equal than the number of own resources available. This condition can be expressed as

$$\sum_{i=1}^{I}\sum_{j=1}^{Ni} XO_{ijkt} \leq R_k \qquad \text{(t= min aij,..., max Gi; k= 1,2,...K)}$$

AUTOMATION OF THE ALLOCATION PROBLEM

The amount of work to solve an allocation problem by using a mathematical approach is considerable. To make use of such approach, the construction practitioner would have to proceed as follows:

1. Once the projects have been broken down into packages, activities duration have to be calculated.
2. Obtain CPM calculations (Early start, early finish etc.) for all activities for every project based on durations and precedence relationships.
3. Develop and solve the model.
4. Translate the answers provided by the model to actual dates.
5. Keep track of the projects under execution.
6. If a new project arrives, a new allocation should take place.

The amount of work required to solve the problem following the mathematical approach is substantial. For example, the schedule produced by the mathematical model is given in terms of periods so no actual dates can be obtained from the model. On the other hand, before developing the model, the CPM calculations required have also to be expressed in terms of periods. Developing the model itself is a time consuming task. All these inconveniences definitely suggest that the solution process and its answers have to be automated.

The main objective in automating the process is to provide a useful and powerful tool to allocate/schedule the equipment by using a mathematical model. On the other hand, this system should have the ability to handle the occurrence of new events so a new decision regarding allocation can be made. The next section will describe the structure and the main features of a programming application developed to automate the allocation process.

STRUCTURE OF THE AUTOMATED SYSTEM

From a practical point of view, for a construction manager who is using the solution process suggested by this research, the bottom line is to be able to generate an "optimum schedule". The system has to be flexible and easy to use.

A system that allows the automation of the allocation process was designed. The system developed has four main components:

- Scheduling Software (Microsoft Project)
- Shell
- Linear Programming Software (LINDO)
- Projects Database

Figure 4-5 shows the relation between the different components of the system.

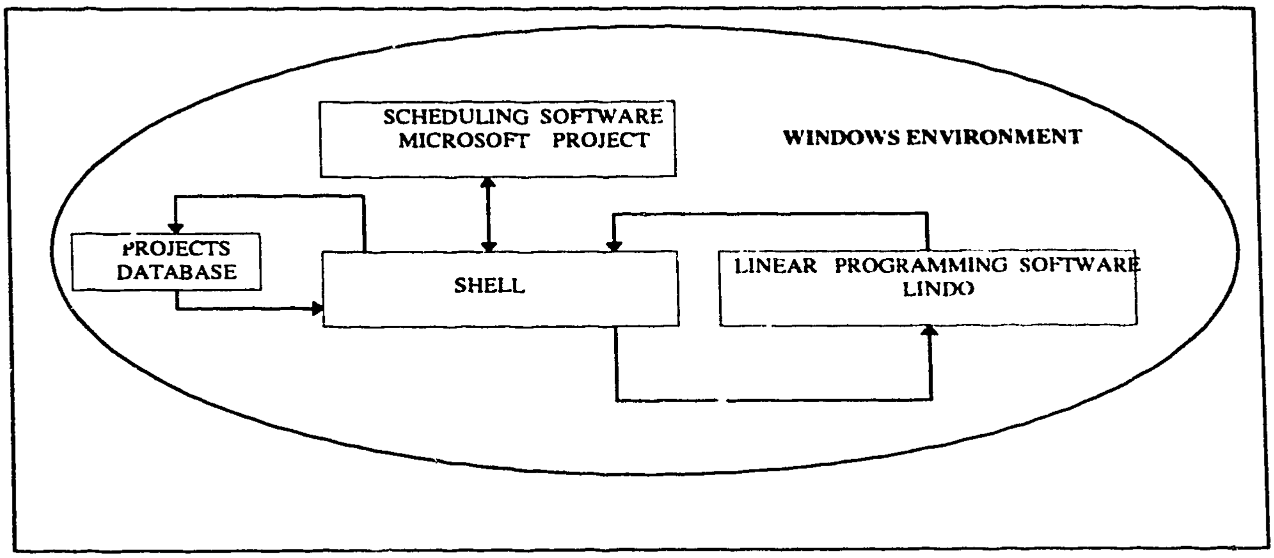


FIGURE 4-5 AUTOMATED SYSTEM

Scheduling Software

Nowadays companies are using scheduling software for project control and project planning. Generally speaking and when properly used, these computer programs are excellent tools for project management. Their displaying and reporting features also make them very useful.

Usually the schedules generated by this kind of software are based on the Critical Path Method (CPM). Once the duration of activities and the precedence relationships are entered the program automatically calculates the critical path. CPM calculations include early start, early finish, late start and late finish for every activity. These programs also have the ability to handle information about the resources required to perform a task. By using these programs it is also possible to create a resource pool to carry out different projects. This allocation is done by leveling, which is basically an heuristic method for allocation of resources. However this way of allocation does not always guarantee reasonable results. These rules do not always have the same performance for all kind of projects. In order to provide the calculations required to generate the model and also because of its characteristics to interact with other programs it was decided to use Microsoft Project as part of the automated system.

In summary Microsoft Project is used to obtain the calculations required in order to create the mathematical model and if necessary to keep track of projects as well as for generation of reports.

Shell

The shell is the heart of the system. This component makes possible to integrate all the other elements in such a way that the user only has to deal with one system. The shell is a program written in Visual Basic 3.0 which is a event driven language. The main modules and its structure will be discussed in the following sections.

Linear Programming software

The model automatically generated by the shell is solved by LINDO. Lindo is a software for linear programming, mixed integer linear programming and quadratic programming. It uses simplex and active set algorithms for linear and quadratic programming, and a branch-and-bound approach for mixed integer programming.

The smallest version of LINDO can handle up to 100 constraints and 200 variables, while the largest extended LINDO handles up to 32000 constraints and 100000 variables.

The PC version includes a full-screen editor and a pop-up window that allows the progress of the algorithm to be monitored.

Projects Database

In order to facilitate the manipulation (storing and retrieving) of the information about the projects under execution and new projects a relational database was created. A relational database allows the inclusion of several tables that can be linked to each other in a way that entering and retrieving information can be done in a very efficient way. Figure 4-6 shows the structure of the database which basically consists of six tables. Tables are linked to each other by using common fields.

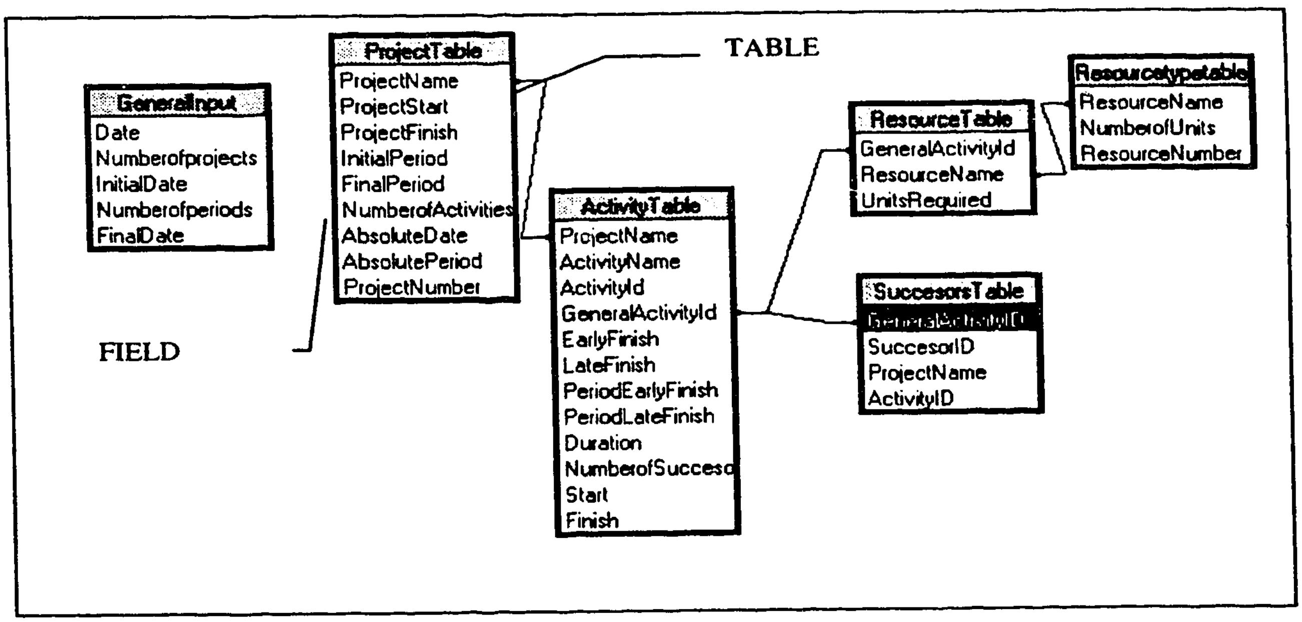


FIGURE 4-6 PROJECTS DATABASE STRUCTURE

Once the information is in the database, retrieving and updating the information about the projects can be done more efficiently.

In summary once an initial schedule is obtained from Microsoft Project the shell will generate the mathematical model. Then the linear programming software (LINDO) is invoked to solve the model and the answers are sent back to the shell to be translated.

Finally the shell sends back these answers to Microsoft Project so the old schedule can be updated. In other words the system developed has the ability to access and to update the schedule contained within the scheduling software at any given time.

SHELL

One of the main concerns in developing a program is the creation of its interface. A successful automation requires an efficient and friendly interface. The shell was completed by using Microsoft Visual Basic 3.0 which is an event driven language for the windows environment. Visual Basic also supports object oriented concepts which make programming easier and more efficient. In conjunction with the visual basic program, a relational database is used to store project information and to handle the arrival of new events. The main functions of the program are:

- Exchanging information with the scheduling software
- Generating the mathematical model
- Graphically displaying the optimization results
- Generating reports about current and optimum solutions
- Handling the occurrence of new events
- Storing information about the optimization process

One of the important aspects in automating the whole process is retrieving information from the scheduling software to create the mathematical model. It was discussed before that CPM calculations are required and once they are obtained it is necessary to translate dates to sequential numbers since the model uses period number as time reference. The link between the shell and Microsoft Project is achieved by using object oriented concepts.

A detail description about this and other features of the system are described in the following sections.

Structure of the shell

Figure 4-7 shows the flow diagram of the program. Basically the program starts with an initial situation with no projects under execution. Initial projects are selected and information for these projects (CPM calculations and resource requirements) is retrieved from MS Project. Once this information is obtained the mathematical model is generated. and LINDO is invoked to solve the model.

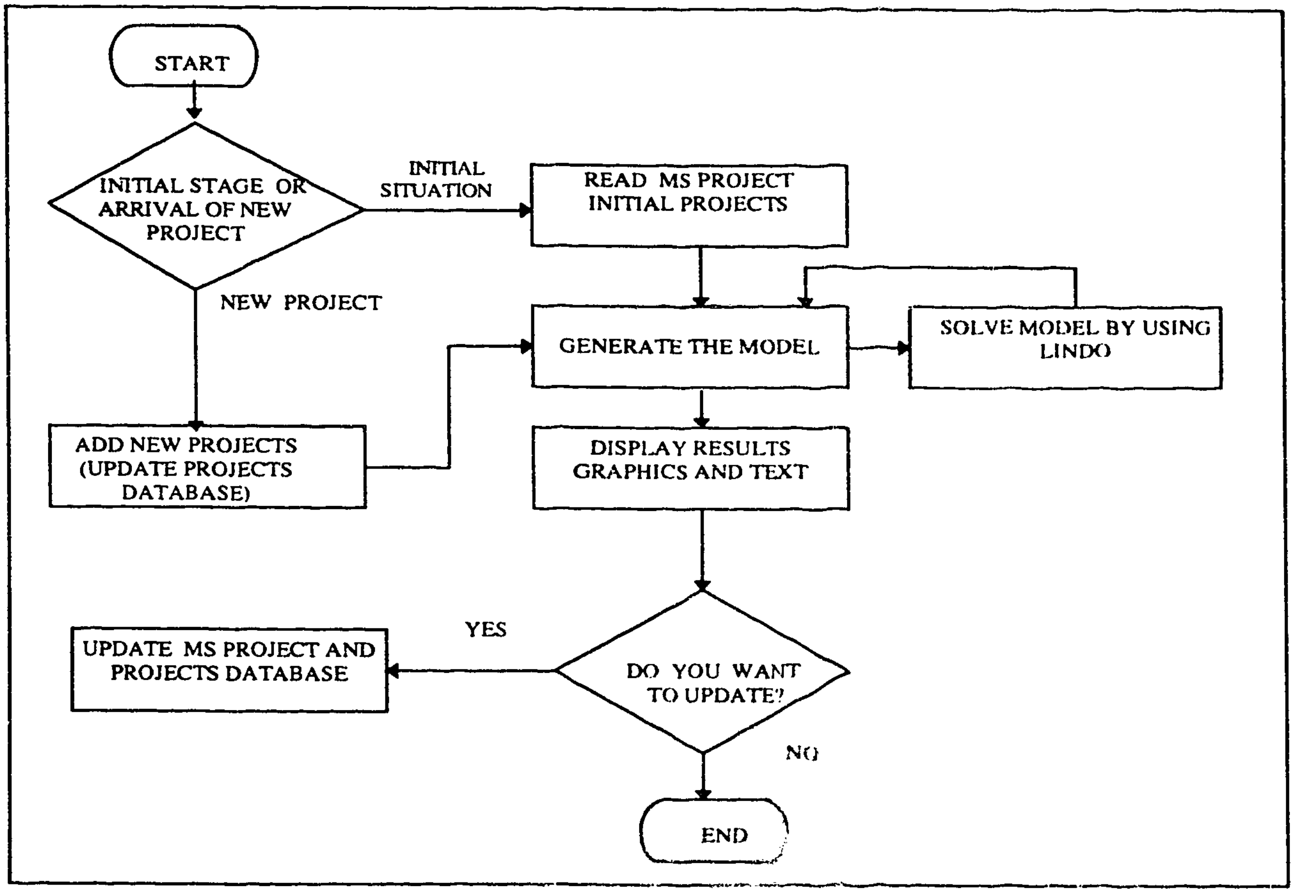


FIGURE 4-7 FLOW DIAGRAM

Then the solution to the model given by LINDO is used to generate the optimum schedule. This schedule is displayed both in a graphical and in a textual manner. At this point, based on the optimum solution the schedule in MS Project as well as the database can be updated. When a new project arrives this is added to the projects database. Then the mathematical model is generated and the same procedure is repeated.

The shell has three main modules. The first module retrieves the information from Microsoft Project. The second module develops and solves the model. The third module displays the results in a graphical and textual way.

Linking the shell and the scheduling software

As it was pointed earlier the connection between Microsoft Project and the shell was achieved by using object oriented concepts. Object oriented technologies have been successfully used to model different problems. A system can be modeled by defining objects. An object will have some properties that will identify it.

One of the main advantages is that it is possible to create a hierarchy of objects. In this way the characteristics or properties of the parent object will be inherited by the children objects. This hierarchy makes it possible to access information in a very fast and efficient way.

Both Microsoft Project and Visual Basic support object oriented concepts. Projects and all their information can be modeled using object oriented concepts. Figure 4-8 describes the object model and its hierarchy used by Microsoft Project. A general object which will contain all projects must be initially defined. This is called a Microsoft application object. Once this object is created it is possible to access all other projects and all the information required to build the model (activities, duration, calendars, resources, dates).

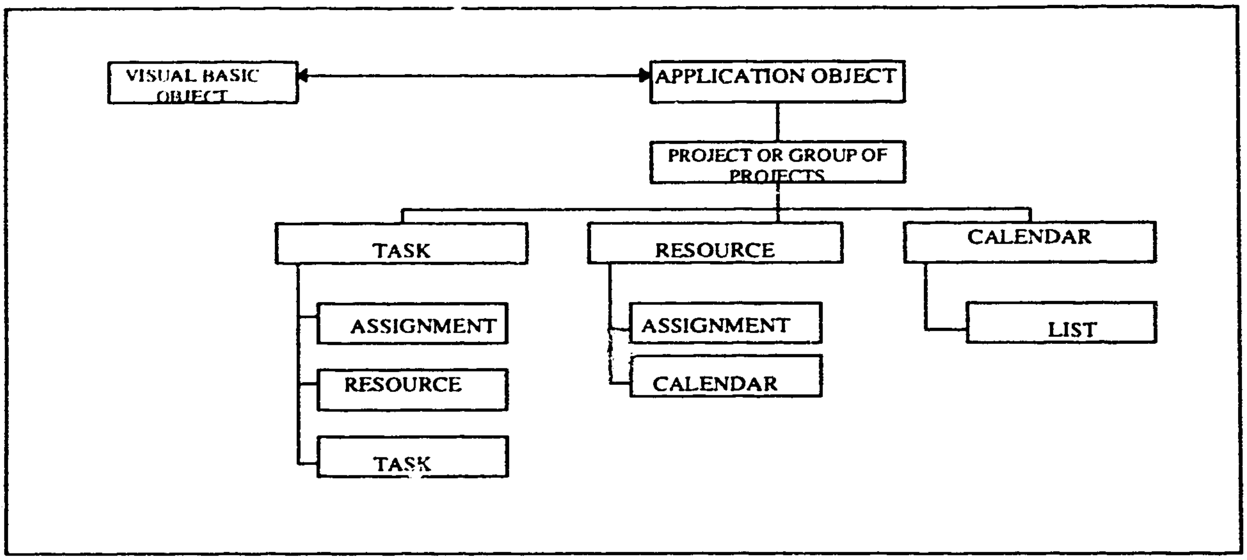


FIGURE 4-8 OBJECT HIERARCHY

INTERFACE STRUCTURE

The hierarchy of the interface and possible course of actions to follow once the program is run are shown in Figure 4-9.

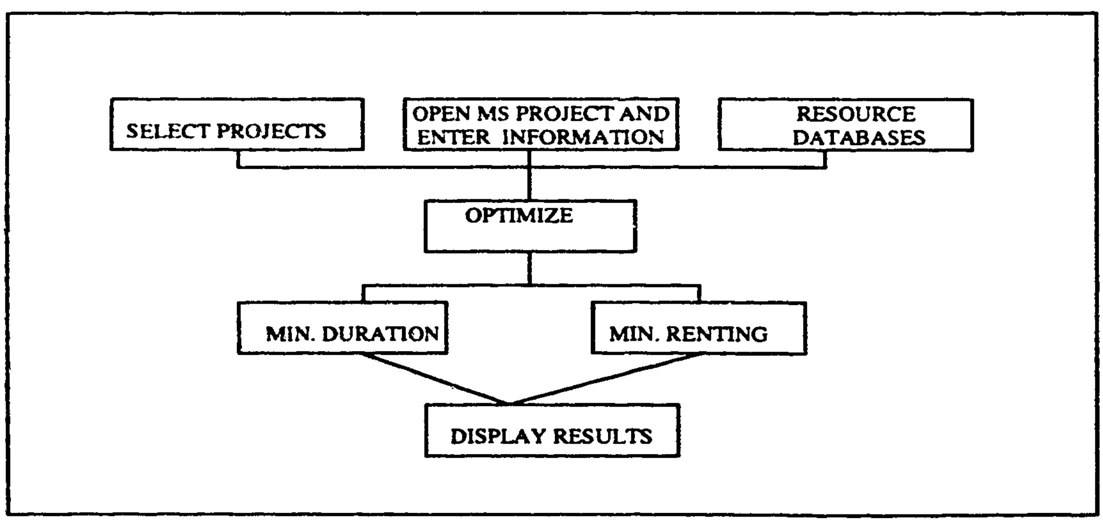


FIGURE 4-9 INTERFACE HIERARCHY

When the program is run a main menu appears on the screen. At this point the user has three options:

- Select projects (Figure 4-10). Project selection is done by double clicking on a specific project on the " project selection window".
- Open MS Project and input all information required for the optimization and
- Edit database resources

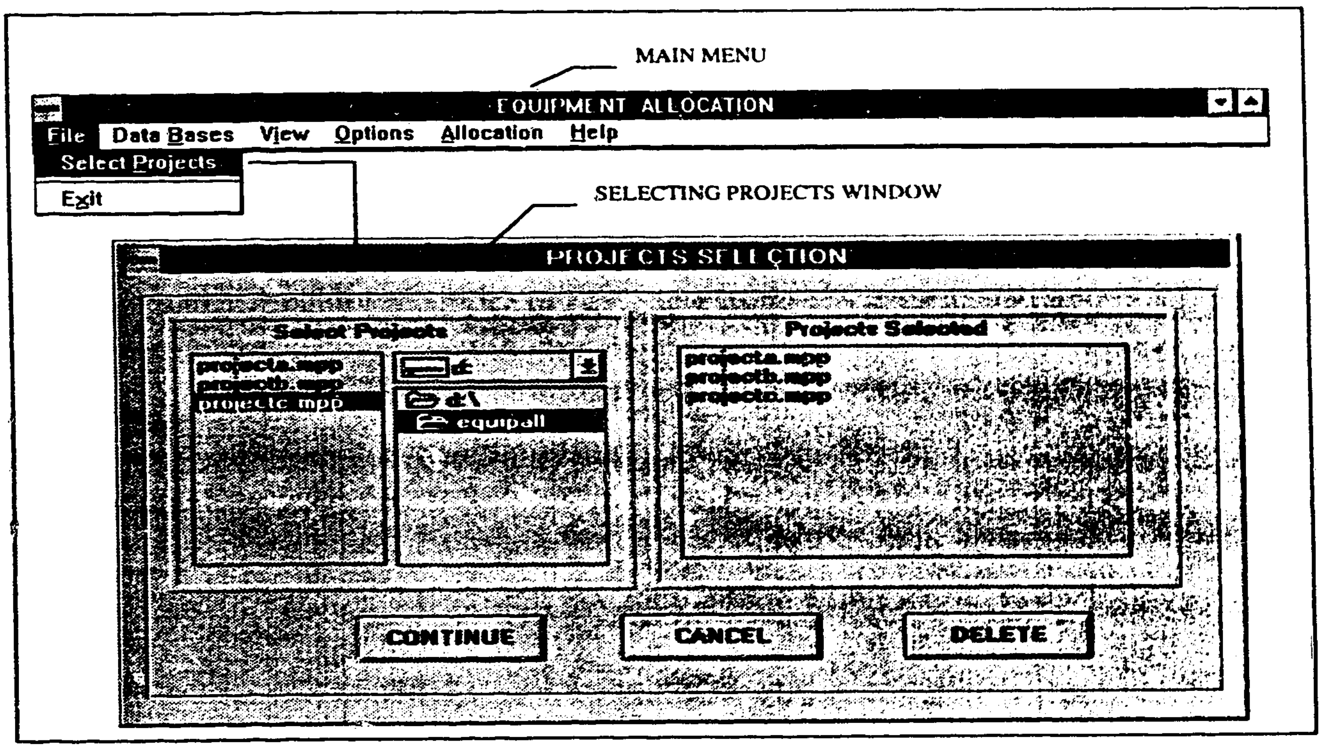


FIGURE 4-10 SELECTING PROJECTS WINDOW

After the user has decided what projects to analyze then the optimization process can be initialized by choosing between minimizing the total duration or minimizing the renting. Figure 4-11 shows the main menu with the projects editing and allocation options.

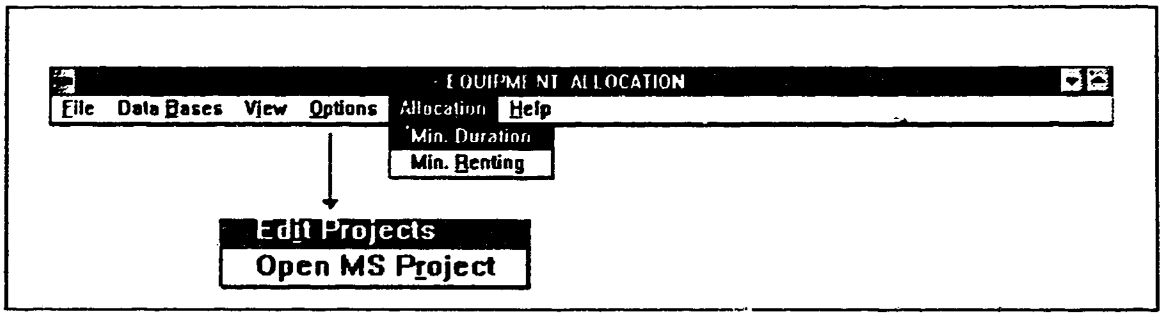


FIGURE 4-11 PROJECTS EDITING AND ALLOCATION OPTIONS

Once the optimization is done the solution is displayed graphically by showing the optimized schedule and textually by showing all the information related to the projects.

At this point the user can generate reports and update the projects' database as well as the old schedule in MS Project.

CASE STUDY

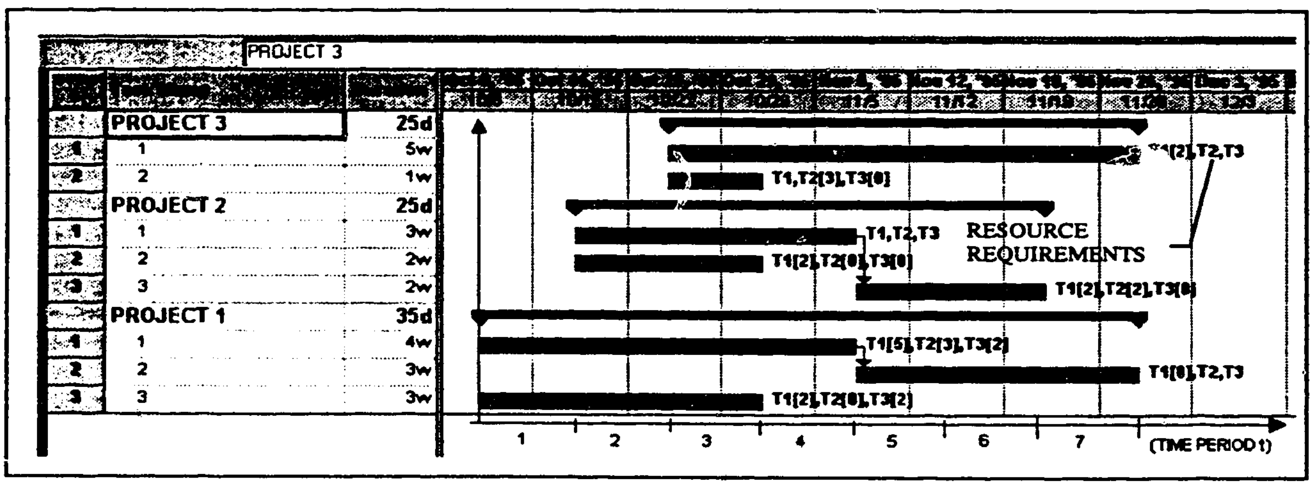


FIGURE 4-12 INITIAL SITUATION

Figure 4-12 shows the initial conditions for a three-project, eight activities, three resource type problem. Table 4-1 contains activity duration, precedence relationships and resource requirements.

Project i	Activity j	Precedence Relation (i,j)	Duration (d_{ij})	Absolute Due Date (G_i)	Resource Req. (r_{ijk}) k=1	k=2	k=3
1	1	None	4	8	5	3	2
1	2	1,1	3	8	0	1	1
1	3	None	3	8	2	0	2
2	1	None	3	9	1	1	1
2	2	None	2	9	2	0	0
2	3	2,1	2	9	2	2	0
3	1	None	5	9	2	1	1
3	2	None	1	9	1	3	0
Amount of Resource k available in each period (R_{kt})					8	5	4

TABLE 4-1 PROJECTS INFORMATION

The information shown in table 4-1- and Figure 4-12 has to be entered in Microsoft Project. As soon as the program is run the projects have to be selected (Figure 4-10). Then the allocation should take place (appendix A shows the linear programming model). To allocate the user has to click in the allocation option and then chose between minimizing duration or minimizing renting. At this stage it is also possible to edit projects information if required. Once the optimization is completed the program will allow the user to graphically and textually display the current situation (Figure 4-13) as well as the "optimum situation". Selecting the option View in the main menu will allow the user to see two windows:

- The current state window and
- The optimization window.

Both windows have three tabs to display information:

- Project schedule tab: displays the current or the optimized schedule. (Figure 4-14)

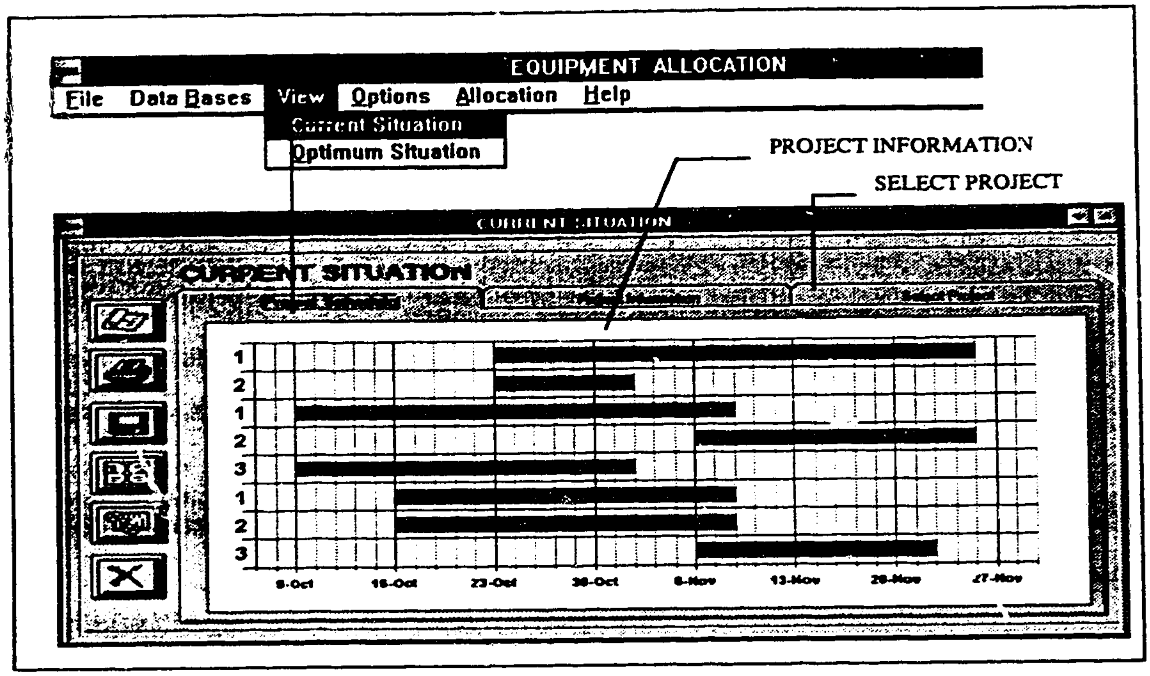


FIGURE 4-13 CURRENT SITUATION

- Select Project tab: displays all projects information. The user can select a project by highlighting it.(Figure 4-15)

- Project Information: displays current or optimize information about the project selected in the select project tab.

Project	Activity	Variable	Completion Period	DATE
1	1	X_{114}	4	NOV. 8
1	2	X_{127}	7	NOV. 28
1	3	X_{137}	7	NOV. 28
2	1	X_{214}	4	NOV .8
2	2	X_{226}	6	NOV .22
2	3	X_{236}	6	NOV .22
3	1	X_{317}	7	NOV .28
3	2	X_{327}	7	NOV .28

TABLE 4-2 COMPLETION PERIODS GIVEN BY THE MODEL

Table 4-2 shows the activities and the variables that indicate the completion period for each activity. These are the results provided by LINDO that are used to produce the optimum schedule.(Figure 4-14)

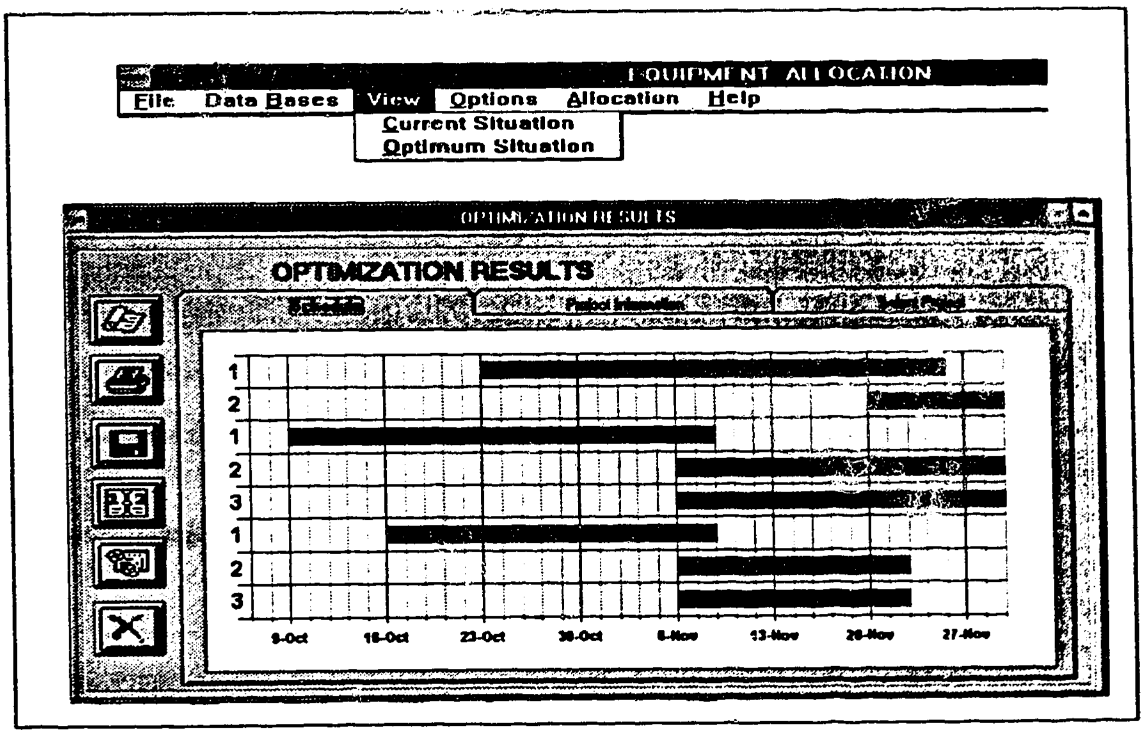


FIGURE 4-14 OPTIMUM SCHEDULE

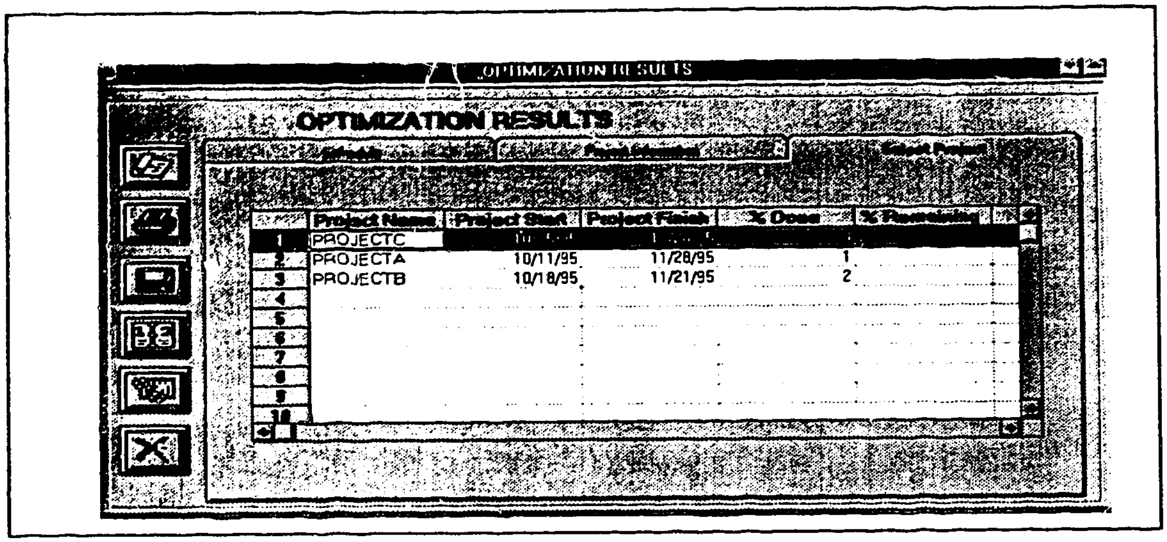


FIGURE 4-15 PROJECT SELECTION TAB

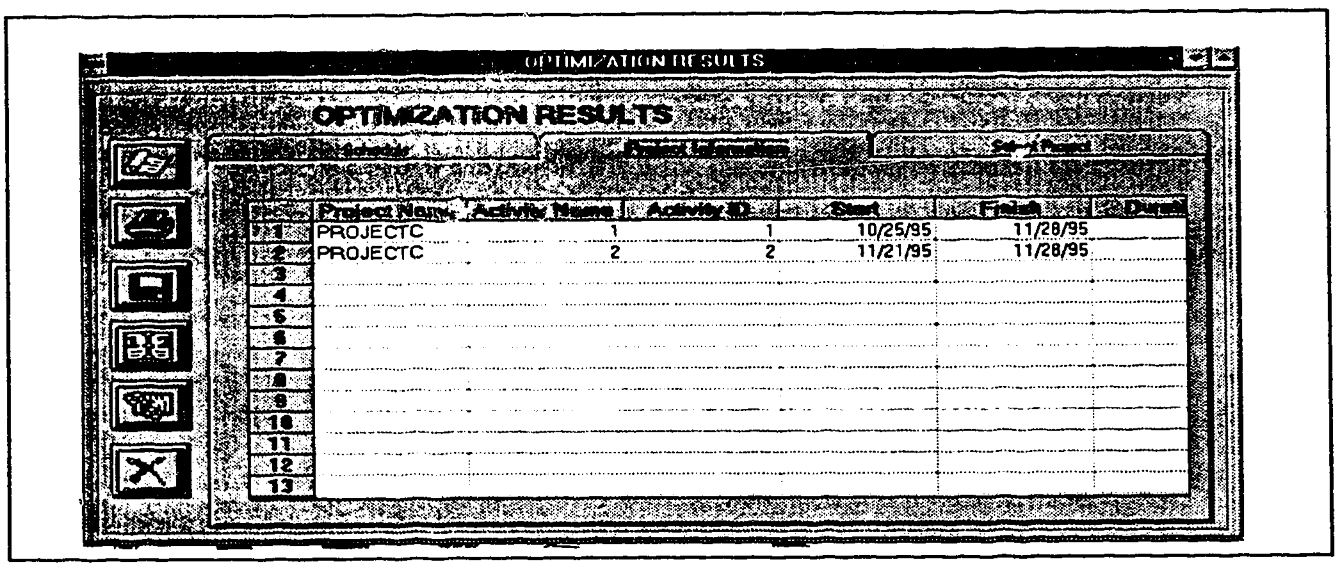


FIGURE 4-15 PROJECT INFORMATION TAB

Validation of the model

In order to validate the model this example was solved using Microsoft Project. Microsoft Project allows the allocation of limited resources to multiple projects using a technique called leveling. In general, leveling resolves resource conflicts (amount of resources required is larger than the amount of resources available) by delaying certain tasks. As it was discussed before some heuristics are used for this purpose. The results of this leveling are shown in Figure 4-16.

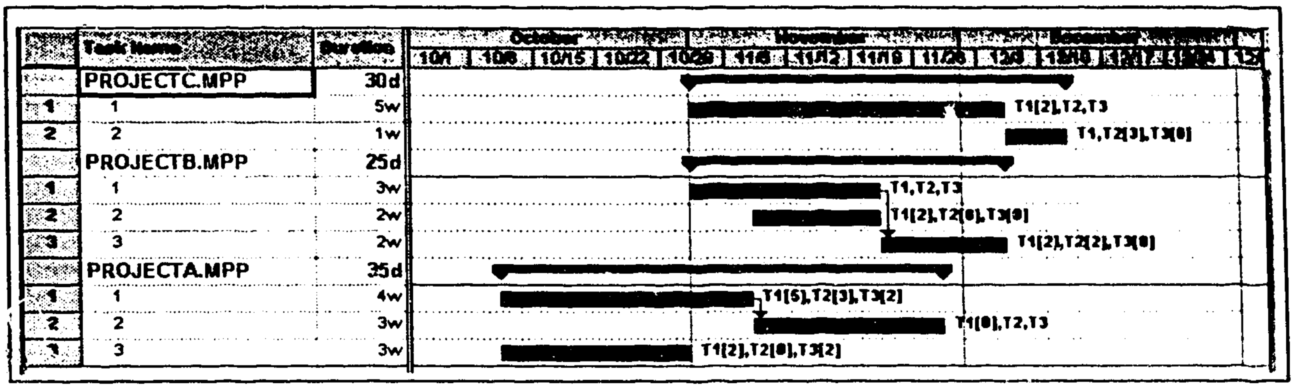


FIGURE 4-16 MS PROJECT LEVELING

The total time time required to finish all the projects according to MS Project is 9 weeks whereas the linear programming model shows that the required time is only 7 weeks.

CONCLUDING REMARKS

A computerized application was developed to solve the equipment allocation problem. The application has three main components: *i. A scheduling software, ii A linear programming software and a Visual Basic program.*

One of the most important futures of the system is its ability to retrieve and send information from the scheduling software (MS Project). This is done by using object oriented concepts. This technology allows to represent models in a hierarchical way. In this case the projects and their properties are represented also in a hierarchical way.

The developed system allows the construction practitioner to try different alternatives before making a final decision.

A system like the one developed makes it possible to use linear programming formulations in actual cases. Another advantage is that the user does not have to know about mathematical models to use the system.

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APPENDIX A LINEAR PROGRAMMING MODEL FOR EQUIPMENT ALLOCATION

MAX TIME
S.T.
65TIME-65x18-65x27-65x28-65x29-65x38-
65x39+4x114+5x115+7x127+8x128+3x133+
4x134+5x135+6x136+7x137+8x138+4x214+
5x215+6x216+7x217+3x223+4x224+5x225+
6x226+7x227+8x228+9x229+6x236+7x237+
8x238+9x239+7x317+8x318+9x319+3x323+
4x324+5x325+6x326+7x327+8x328+9x329=0
x114+x115=1
x127+x128=1
x133+x134+x135+x136+x137+x138=1
x214+x215+x216+x217=1
x223+x224+x225+x226+x227+x228+x229=1
x236+x237+x238+x239=1
x317+x318+x319=1
x323+x324+x325+x326+x327+x328+x329=1
x114+x115+x127+x133+x134+x135+x136+
x137>=3x18
x214+x215+x216+x223+x224+x225+
x226+x236>=3x27
x214+x215+x216+x217+x223+x224+x225+
x226+x227+x236+x237>=3x28
x214+x215+x216+x217+x223+x224+x225+
x226+x227+x228+x236+x237+x238>=3x29
x317+x323+x324+x325+x326+x327>=2x38
x317+x318+x323+x324+x325+x326+x327+
x328>=2x39
4x114+5x115-7x127-8x128=-3
4x214+5x215+6x216+7x217-6x236-7x237
-8x238-9x239=-2
5x114+2x133<=8
3x114<=5
2x114+2x133<=4
5x114+5x115+2x133+2x134+1x214+
2x223<=8
3x114+3x115+1x214<=5
2x114+2x115+2x133+2x134+1x214<=4
5x114+5x115+2x133+2x134+2x135+
1x214+1x215+2x223+2x224+2x317+1x323<=8
3x114+3x115+1x214+1x215+1x317+3x323<=5
2x114+2x115+2x133+2x134+2x135+1x214+
1x215+1x317<=4
5x114+5x115+2x134+2x135+2x136+
1x214+1x215+1x216+2x224+2x225+
2x317+2x318+1x324<=8
3x114+3x115+1x214+1x215+1x216+1x317+1x318+
3x324<=5
2x114+2x115+2x134+2x135+2x136+1x214+
1x215+1x216+1x317+1x318<=4

5x115+2x135+2x136+2x137+1x215+1x216+
1x217+2x225+2x226+2x236+2x317+2x318+
2x319+1x325<=8
3x115+1x127+1x215+1x216+1x217+
2x236+1x317+1x318+1x319+3x325<=5
2x115+1x127+2x135+2x136+2x137+1x215+
1x216+1x217+1x317+1x318+1x319<=4
2x136+2x137+2x138+1x216+1x217+2x226+
2x227+2x236+2x237+2x317+2x318+2x319+
1x326<=8
1x127+1x128+1x216+1x217+2x236+2x237+
1x317+1x318+1x319+3x326<=5
1x127+1x128+2x136+2x137+2x138+1x216+
1x217+1x317+1x318+1x319<=4
2x137+2x138+1x217+2x227+2x228+2x237+
2x238+2x317+2x318+2x319+1x327<=8
1x127+1x128+1x217+2x237+2x238+1x317+
1x318+1x319+3x327<=5
1x127+1x128+2x137+2x138+1x217+1x317+
1x318+1x319<=4
2x138+2x228+2x229+2x238+2x239+2x318+
2x319+1x328<=8
1x128+2x238+2x239+1x318+1x319+3x328<=5
1x128+2x138+1x318+1x319<=4
2x229+2x239+2x319+1x329<=8
2x239+1x319+3x329<=5
1x319<=4

CHAPTER 5: CONCLUSION

SUMMARY OF THESIS WORK

Although operations research techniques have been successfully implemented in other fields, e.g., manufacturing, their use in construction has been minimal. This is mainly due to the fact that the generation of the models that can represent the complexities of construction processes is difficult and time consuming.

The main objective of this research was to develop a framework that could facilitate the application of operations research concepts (specifically linear programming formulations) to the fields of concrete mix design and equipment allocation. This resulted in the development of two computer programs which demonstrated the applicability of the linear programming concepts to the solution of real-world problems.

The programs developed consisted of three main components: a database component, an input component and a reporting component. The input component facilitates obtaining inputs from the user, the database component stores raw data and the results of intermediate processing of the raw data and the reporting component presents the results obtained from the program to the user.

The systems were developed for Microsoft Windows 3.0. In both cases LINDO (commercial software for linear programming formulations) was used to solve the models.

Concrete mix design:

An automated system based on a linear model proposed by Rashwan et al was developed. The optimization is based on several relationships that describe the influence of different variables affecting the concrete manufacturing process. The objective was to minimize the cost. These relationships (constraints) were derived from historical information. When designing a new mix, the system retrieves all the mixes of relevance done in the past from the his.orical database and based on this information generates relationships. The parameters (slope and intercept) of these relationships can be changed before the model is developed. The program computes the optimum amounts of ingredients as well as predicted values for the quality control parameters (slump, strength and air content).

Equipment Allocation:

The system developed combines a linear programming model and a scheduling software package to determine the best course of action for different projects according to a given objective function. Results of CPM calculations serve as inputs to the model. These calculations are retrieved automatically from the scheduling software. The system has a database that contains information about the current and optimum situations once the linear programming model is solved. This system allows the user to try different alternatives (selecting different date lines) before making final decisions. The updating of the schedule is also done automatically. The results are displayed in textual as well as graphical formats.

SIGNIFICANT RESULTS

This work has provided the necessary framework required to apply linear programming models in the fields of concrete mix design and equipment allocation. We have developed conceptual models as a basis for the development of automated systems that make use of linear programming concepts.

The equipment allocation problem was studied by combining a linear programming model and a scheduling software package used for project management. Such an arrangement facilitates the analysis of the equipment allocation problem under different scenarios. An automated system such as this, facilitates the updating of different schedules used by construction managers.

The two case studies have demonstrated the applicability of linear programming techniques for developing comprehensive models of the mix design and equipment allocation problems and also for arriving at optimum solutions to these problems.

FUTURE RESEARCH DIRECTIONS

Concrete manufacturing includes several processes: design, manufacturing and delivery. All these elements should be considered as a whole and not in an isolated context. The general framework required to link the mix design process, that uses a mathematical model, to other relevant process such as batching and delivery needs to be developed. An extension to this work would be to develop a general system that incorporates all these components in one single system.

The equipment allocation model assumes that the equipment required for a particular task is known. However, in real world situations this is often not the case. Project personnel like superintendents and estimators have to decide on the best combination of equipment required for the task. A useful extension to this work would be to make the model flexible enough to facilitate its use in what- if analysis.

Another enhancement to the equipment allocation problem is the incorporation of a probabilistic approach for the activities' duration.

FINAL REMARKS

This research work has demonstrated the use of linear programming concepts in the fields of concrete mix design and equipment allocation. Based on conceptual models computer programs were developed in these fields. The programs developed are currently in the final stages of implementation. The equipment allocation program has been incorporated as part of a general productivity-improvement project within the collaborating company.

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