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MATHEMATICAL MODELING FOR BUILDING DESIGN OPTIMIZATION

[1] PROF.DR. SUMIT KUMAR BANERJEE
[2] MR. S. PALANIAPPAN

[1] PROFESSOR & DEAN (RESEARCH & DEVELOPMENT)
DHIRAJLAL GANDHI COLLEGE OF TECHNOLOGY (DGCT)
SALEM-636309, TAMIL NADU, INDIA

[2] ASSOCIATE PROFESSOR (DEPARTMENT OF CIVIL ENGINEERING)
DHIRAJLAL GANDHI COLLEGE OF TECHNOLOGY (DGCT)
SALEM-636309, TAMIL NADU, INDIA

Abstract:
In this research a method for solving the decision in building plan design by using mathematical model based on non linear programming has been analyzed. Here our first objective is to formulate non linear mathematical models for analyzing the division of rooms and their dimensions in a building plan and thereafter to calculate the dimensions of room sizes which have minimum construction cost. A case study of condominium building plan is also analyzed.

Key words: Building plan, non linear programming, mathematical model, construction cost, condominium

1.0 Introduction

Design is the creation of a plan for the construction of an object or a system. This represents a process in which intelligence and creativity are applied to a project in order to achieve an efficient and elegant solution. Design encompasses functional efficiency, structural integrity, sustainability, lifetime costing and flexibility as well as responsiveness to the site and to its

setting. Good design involves creativity and it should lead to simplification and to savings in cost. It can increase outputs and add to the quality of service. It can always give the facility a competitive advantage in attracting both customers and staff. Good design can also contribute to wider policy objectives, such as those relating to the protection of the environment. Good designs add values in functionality, reducing whole-life costs, service enhancement, and architectural quality and wider social and environmental benefits. Generally architectural design uses combination of knowledge both artistic and scientific to create a balance between the functions aesthetics and economics of buildings. Building plan design is a part of architectural design which uses the knowledge. A construction unit cost method which generally used is unit cost method which is value of total output, the value called unit cost. In construction business unit cost is construction cost per usable area of the building construction. Generally construction unit cost comes from three parts of cost including materials, labors and machines. Nonlinear programming technique designed to optimize the usage of limited resources. Successful applications of nonlinear programming exist in the areas of military, industry, agriculture, transportation, economics, health systems and even behavioral and social sciences. In this research problem is to solve decision in building plan design. First we divided rooms and dimensions in a building plan of a building case study. The differences of construction costs for each part of the buildings have effect to total construction cost of the building through different design patterns of the building plan. Thus nonlinear programming model can be used to solve the problem. Outputs of the model were to find out the minimum cost for construction and appropriate usable area in the building within design constraints.

1.1 Objectives

- To formulate mathematical models for analysis in dividing rooms and dimensions in a building plan of a building case study.
- To calculate and find out the dimensions and room sizes which have minimum construction cost

1.2 Scope of study

Scope of this research covered analysis and design of a condominium building plan where the mathematical model technique has been applied on comprised of seven rooms. The seven rooms including: (i) Dining hall (ii) Kitchen (iii) Toilet (iv) Drawing room (v) Bed room 1 (vi) Bed room 2 (vii) Bed room 3.

Construction cost comprised of two parts. Firstly, construction cost of floors considering unit costs of construction per usable area $\left(Rs./m^2\right)$ by classifying functions of each room. Secondly construction cost of walls considering unit costs of construction per wall area $\left(Rs./m^2\right)$ by classifying types of external and internal walls. Following Fig.1 is a bubble diagram which representing relationships between areas in the building plan [1].

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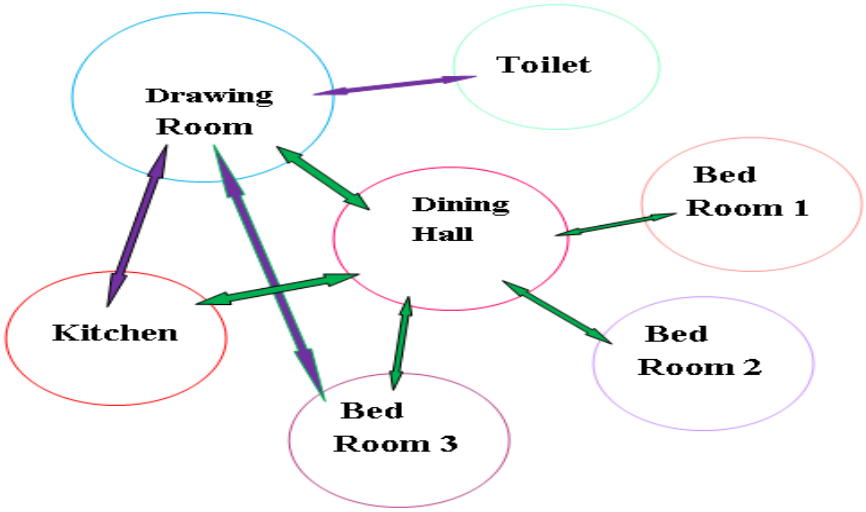

Fig. 1: Relationships between the areas in the building plan

Following Fig. 2 representing the preliminary plan of the building before analysis.

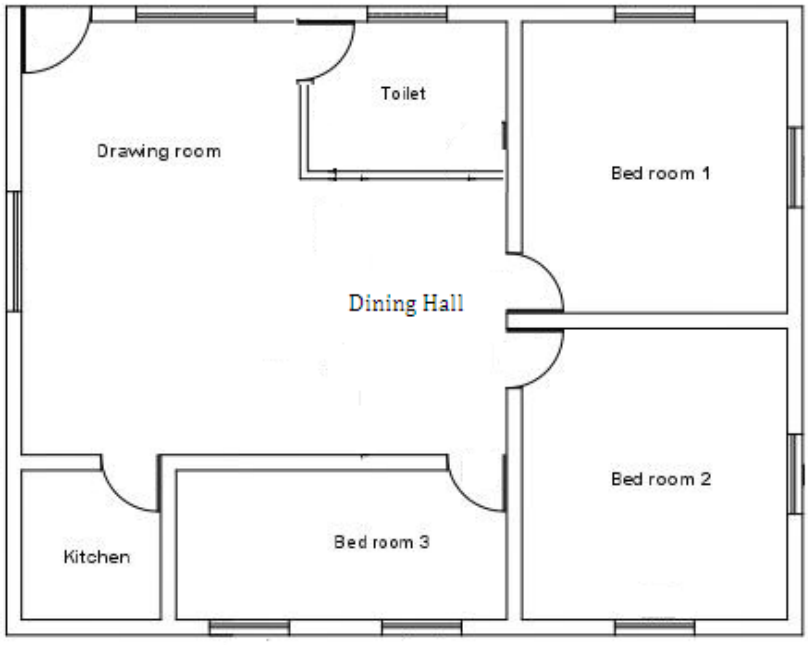

Fig. 2: Preliminary plan of the condominium building

2.0 Literature Review

Building plan design is a part of architectural design which uses combination of knowledge both artistic and scientific for creation a balance between the functions, aesthetics and economics of the building. The design process is often described as an orderly arrangement of phases or steps. Yet designers should not think of these steps as having absolute start and stop points. Not all projects require a designer to go through all the steps, but most benefit from following the process. Each phase is also requires thinking critically, working to solve the problem and making decisions to complete the project. The knowledge gained in academic programs provides a foundation for these skills in design. The design process involves numerous activities and tasks

to bring about a solution. Some involve working with clients and other involved in the project. As for the design process itself, it has been recognized to involve five phases (as shown in Fig. 3) namely, Design programming, Schematic design, Design development, Contract documents and Contract administration.

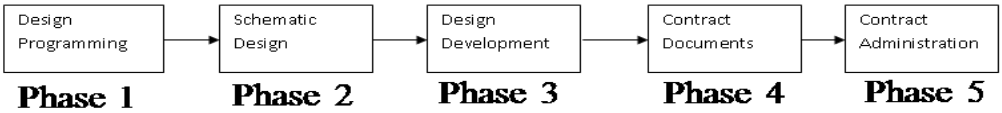

Fig. 3: Five phases of the design process

Design programming is considered the information-gathering phase. The designer seeks to obtain as much information as possible concerning the responsibilities outlined in the scope of services. Depending on the project, information will be gathered from client, employees, project architect, municipal departments and others as might be needed.

Schematic design is a design where preliminary planning and early decision making takes place. Bubble diagrams, adjacency diagrams and concept sketches are common visual documents.

Design developments are the stage where the designer finalizes with the client many decisions concerning the project. For example the designer will provide detail floor plans to ensure that space plans will work and furniture will fit.

Contract documents are the construction and installation drawings, specifications and required documents needed to get the project built and installed. Dimensioned floor plans, lighting/reflected ceiling plans and finish schedules represent some of these items.

Contract administration involves the competitive bidding or placing of orders for the work and items to be built and installed. Competitive bidding commonly occurs for commercial projects such as offices. For smaller projects and many residential projects the designer might be responsible for procuring the goods and services needed to complete the project [2].

In construction cost estimations, Ostward (2001) [3] stated that the unit method is the most convincing of all estimating methods. Examples of unit estimates are found in many business and economic activities such as cost of house, construction per square foot, cost of electrical transmission per mile, construction cost per hospital bed, chemical plant cost per barrel of oil capacity. Area is perceived to have a powerful effect upon costs and thus its popularity. The unit method is used extensively such as average material prices, man hours and labor cost. The unit estimate is defined as the mean where the divisor is the principal cost driver.

The rules for calculating the area are:

- All measurements are taken from the internal face of external walls. No deduction is made for internal walls, lift stair wells etc.
- Where different parts of the building vary in function then the areas are calculated separately.
- External works and non-standard items such as piling are calculated separately and then added into the estimate. Figures for specialist works may be available from sub-contractors and specialist contractors.

2.1 Linear Programming

Linear programming is a mathematical modeling technique designed to optimize the usage of limited resources. Successful applications of linear programming exist in the areas of military, industry, agriculture, transportation, economics, health systems and social sciences [4]. However not all problems of allocating limited resources can be formulated to fit a linear programming model even as a reasonable approximation. When one or more of the assumptions of linear programming is violated seriously, it may then be possible to apply another mathematical programming model instead of linear programming. E.g. the models of integer programming or nonlinear programming [5]. In fact many problems are nonlinearity in the real world therefore it often is necessary to deal directly with nonlinear programming problems.

Balachandran in 1996 [6] presented an application of multi-criteria optimization which is a nonlinear programming in design of a building plan. Objective functions in the study were minimized construction cost, maximize usable area and aspect ratio of building area. Constraint functions in the study were requirements of dimensions and room sizes.

2.2 Nonlinear Programming

Nonlinear programming is a mathematical model whose objective function and constraint functions are nonlinear. Benefits and applications of nonlinear and linear programming are similar. Presently linear and nonlinear programming software are generally used in personal computers for solving complex problems.

3.0 Research Methodology

Research methodology consists of three parts including: problem formulation, data collection and model formulation.

3.1 Problem Formulation

Problems in building plan design were studied and found that the construction cost comprised of two parts. First part is the construction cost of floors by considering different unit costs of floor constructions for different functions of each room. Second part is the construction costs of walls by considering different unit costs of wall construction for different types of external and internal walls. The differences of construction costs for each part of the building have effect to total construction cost of the building through different design patterns of the building plan.

3.2 Data Collection

After formulation of the problem data are generally used in analysis of the problems which researcher took to formulate the mathematical models of nonlinear programming, included the following points:

- From the preliminary plan of the building setting up decision variables into all dimensions in the building plan along horizontal and vertical axis.
- Collection data regarding owner requirements in dimensions and room sizes of the building plan.
- Collection data regarding building laws and regulations.
- Collection data regarding unit costs of wall construction for external and internal walls.

- Collection data regarding unit costs of floor construction for each function of the seven rooms.

Table 1: Constraints in the condominium building plan design:

Rooms	**Design constraints**
Drawing Room	Owner requirements: Drawing Room should be at least $5m$ of width and length
Kitchen	Owner requirements: Kitchen should be at least $2m$ of width and length and at least $6m^2$ of area
Toilet	Owner requirements: Toilet should be at least $1.5m$ of width and length and at least $3m^2$ of area
Dining Hall	Owner requirements: Size of doors opening to bed room 1 and 2 should be at least $0.9m$ per room according to the size of the doors.
Bed Room 1,2,3	Owner requirements: Each Bed Room should be at least $2.5m$ of width and length and at least $8m^2$ of area. All the Bed Rooms should be of same sizes.

Next, construction cost comprised of two parts. Firstly construction cost of floors considering unit costs of construction per usable area $\left(Rs/m^2\right)$ by classifying the functions of each room as shown in table 2. Secondly construction cost of walls considering unit costs of construction per wall area $\left(Rs/m^2\right)$ by classifying types of external and internal walls as shown in table 3.

Table 2: Unit costs for construction of floor in the condominium building:

Rooms	**Construction cost**
Drawing room & Dining hall	*Rs.* $5200/m^2$
Kitchen	*Rs.* $9000/m^2$
Toilet	*Rs.* $8700/m^2$
Bed Room 1,2,3	*Rs.* $5000/m^2$

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Table 3: Unit costs for construction of walls in the condominium building:

Walls	**Construction cost**
External Wall	*Rs.* $4500/m^2$
Internal Wall	*Rs.* $3400/m^2$

3.3 Model Formulation

Formulation of mathematical models in this research is nonlinear programming which comprised of three main parts:

3.3.1 Decision Variables

From the preliminary plan of the building the decision variables are set into all dimensions in the building plan along horizontal and vertical axis. We have set X_1, X_2, X_3 and X_4 along horizontal axis and X_5, X_6, X_7 and X_8 along vertical axis.

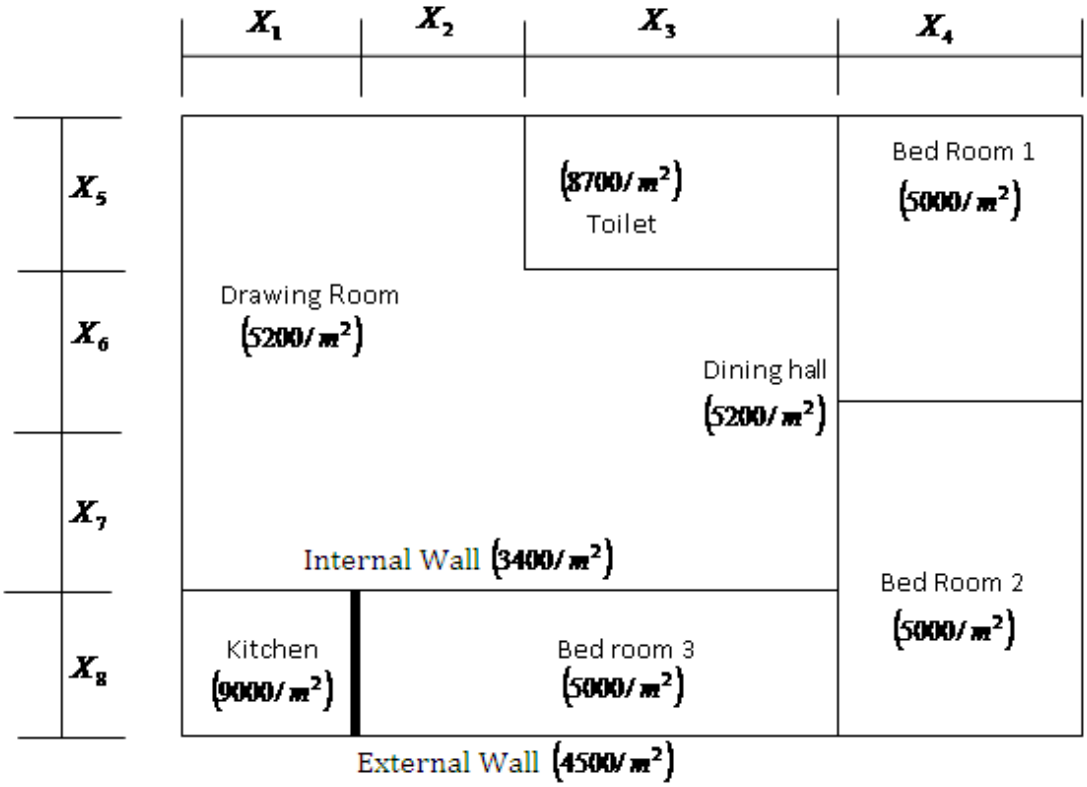

Fig. 4: Preliminary plan of the condominium building with dimensions of decision variables and unit costs

3.3.2 Objective function

Objective function of this research minimizing the construction cost.

$$\text{Minimum cons.cost} = (\text{Drawing room area} \times \text{unit cost of Drawing room}) + (\text{Dining hall area} \times \text{unit cost of Dining hall}) + (\text{Kitchen area} \times \text{unit cost of kitchen}) + (\text{Toilet area} \times \text{unit cost of Toilet}) + (\text{Bed Room 1 area} \times \text{unit cost of Bed Room 1}) + (\text{Bed Room 2 area} \times \text{unit cost of Bed Room 2}) + (\text{Bed Room 3 area} \times \text{unit cost of Bed Room 3}) + (\text{total length of external wall} \times \text{height of external wall} \times \text{unit cost of external wall}) + (\text{total length of internal wall} \times \text{height of internal wall} \times \text{unit cost of internal wall})$$

$$\Rightarrow \text{Minimum cons.cost} = (X_1 + X_2) \times (X_5 + X_6 + X_7) \times 5200 + (X_6 + X_7) \times X_3 \times 5200 + (X_1 \times X_8 \times 9000) + (X_3 \times X_5 \times 8700) + (X_5 + X_6) \times X_4 \times 5000 + (X_7 + X_8) \times X_4 \times 5000 + (X_2 + X_3) \times X_8 \times 5000 + (X_1 + X_2 + X_3 + X_4 + X_5 + X_6 + X_7 + X_8) \times 2 \times 3 \times 4500 + (X_1 + X_2 + 2X_3 + X_4 + 2X_5 + X_6 + X_7 + 2X_8) \times 3 \times 3400 \quad ----------(1)$$

[We have considered the height of internal & external walls as 3 meters (Which is the minimum height required for a building)]

3.3.3 Constraint functions

Constraint functions included owner requirements:

Drawing Room :

$X_5 + X_6 + X_7 \geq 5$ ----------(2)

$X_1 + X_2 \geq 5$ ----------(3)

Kitchen :

$X_1 \geq 2$ ----------(4)

$X_8 \geq 2$ ----------(5)

$X_1 \times X_8 \geq 6$ ----------(6)

Toilet :

$X_3 \geq 1.5$ ----------(7)

$X_5 \geq 1.5$ ----------(8)

$X_3 \times X_5 \geq 3$ ----------(9)

Dining Hall :

$X_6 \geq 0.9$ ----------(10)

$X_7 \geq 0.9$ ----------(11)

Bed Room 1 :

$X_4 \geq 2.5$ ----------(12)

$X_5 + X_6 \geq 2.5$ ----------(13)

$X_4 \times (X_5 + X_6) \geq 8$ ----------(14)

Bed Room 2 :

$X_7 + X_8 \geq 2.5$ ----------(15)

$X_4 \times (X_7 + X_8) \geq 8$ ----------(16)

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Bed Room 3 :

$$X_8 \geq 2.5 \quad \text{----------(17)}$$
$$X_2 + X_3 \geq 2.5 \quad \text{----------(18)}$$
$$X_8 \times (X_2 + X_3) \geq 8 \quad \text{----------(19)}$$

All the bed rooms should be of same sizes

Bed Room 1,2,3 :

$$X_4 - X_8 = 0 \quad \text{----------(20)}$$
$$X_2 + X_3 - X_5 - X_6 = 0 \quad \text{----------(21)}$$
$$X_5 + X_6 - X_7 - X_8 = 0 \quad \text{----------(22)}$$

4.0 Results

Data analysis has been done by using nonlinear programming software (TORA) for the equations (1) to (22) from the model formulation. Following outputs were obtained.

Table 4: Results analysis by using nonlinear programming software

X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	Construction cost (Rs.)	Usable area (m^2)
2.75	2.25	1.50	2.50	2.00	1.75	1.25	2.50	1057000	67.50

From the results the preliminary building plan has been drawn according to the output values of X_1 to X_8.

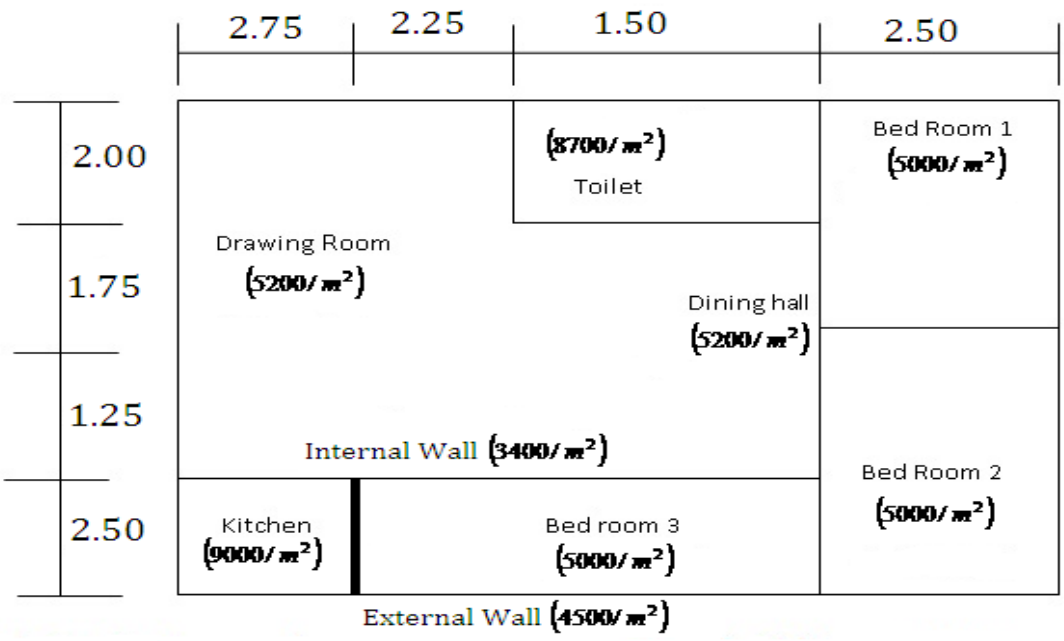

Fig. 5: Condominium building plan with actual value of decision parameters

5.0 Conclusions

This paper presents a method for solving decision parameters in building plan design by using mathematical model on nonlinear programming. Outputs of the model were to find out the minimum cost for construction and appropriate usable area in the building within design constraints such as owner's requirements in room sizes, building laws and regulations, construction costs of floor for each room and external and internal walls by using the unit cost method in construction estimation. A case study of condominium building plan is analyzed and calculated in this research. By using this model an architect will be able to choose the best solution based on the construction cost aspect. This mathematical model can be applied in other more complicated building plans such as a part of circular building plan, triangular building plan or other geometrical shaped building plans. Moreover the constraint functions can be added more other requirements such as required room sizes for furniture sizes or other conditions. The applications of this mathematical model can also be applied to other objective functions such as maximize the usable area in the building within construction cost budget. The objective function can also be set for multi-criteria optimizations such as minimized the construction cost, maximized usable area and aspect ratio of building area.

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