Optimum design of RC affordable housing

Amr Mostafa Hussein Fathy

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School of Sciences and Engineering

“OPTIMUM DESIGN OF RC AFFORDABLE HOUSING”

A thesis submitted to the School of Sciences and Engineering
in partial fulfillment of the requirements for the degree of

Master of Science in Construction Engineering

To

Construction and Architectural Engineering Department

By

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B.Sc. in Construction Engineering, 2013

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February 2015
"Live everyday as if it were your last, but dream, as if you’ll live forever"
ACKNOWLEDGEMENT

I would like to express sincere appreciation to the efforts and support of everyone throughout this journey. The encouragement and support of my mother, father, brother, grandparents, relatives, family members and close friends has kept me energetic, active and persistent in my academic and professional endeavors.

Appreciation goes to my advisors Dr. Khaled Nassar, Dr. Ossama Hosny and Dr. Sherif Safar for their efforts, enthusiasm, encouragement and continuous support. Through their valuable feedback and thorough review of the model, one would be able to improve the model and test its resilience for conformance. I am grateful for the efforts of the advising team in challenging me while believing in my abilities to enhance the research and ensure its potential applicability in the industry.

I would like to thank Dr. Mohamed Abdel Mooty, structural engineering professor, for inspiring me to pursue a concentration in construction materials and structural through his teaching approach that triggers students to think beyond the scope of the course. In addition, for his innovative techniques and efforts made in my five structural engineering courses. Appreciation goes to engineer Ayman Thabit, structural engineering teaching assistant, for his hard work, dedication and determination to instill the structural design concepts and creative thinking through his valuable tutorials.

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Once again, deepest appreciation goes to my mother, father, brother, grandparents, relatives, family members and close friends.
ABSTRACT

Efforts have been made to minimize the cost of affordable housing through modular construction, prefabrication, economies of scale and low cost materials. However, there is a gap in the literature regarding the integration of the varying sizes of the units with design optimization to mutually benefit developers and potential residents of affordable homes. This research introduces an optimization model to integrate optimization with ranges of units’ dimensions.

The model proposed exploits the variations in the reinforced concrete cost versus area through applying several scenarios. Available options are tailored to optimize the reinforced concrete floor cost of housing units through varying the dimensions of the rooms. In addition to this objective, the thesis investigates the sensitivity of selected parameters on the model output. Through these objectives, the model is able to optimize housing units within a specified budget to result in layouts with varying areas where the model would recommend the layout with the least reinforced concrete cost per m2 within the budget range. In addition, it optimizes housing units within a specified area range to result in layouts with varying cost where the model would recommend the layout with the least reinforced concrete cost per m2 in the selected area range.

The model has been applied on 2 case studies where it showed promising results. The research was able to optimize the cost for a given area or increase the area for a given cost. For example, it was able to decrease the cost by 15% for the same area. These percentages are based on the selected examples. Different savings may be achieved with other layouts. However, this is dependent largely on the initial design and dimensions of the unit.
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$w_{\text{bar, total}}$ Weight of steel bars total kg
$A_{s_{\text{secondary}}}$ Area of steel secondary cm$^2$
$W$ Perpendicular length to design direction cm$^2$
$h$ Beam depth m
$L$ Beam length m
$b$ Beam width m
$H$ Floor height m
$\gamma_w$ Unit weight of wall kN/m$^3$
$w$ Weight of wall kN/m$^2$
$w_{\text{wall}}$ Weight of wall kN/m$'$
$\gamma_{\text{plaster}}$ Unit weight of plaster kN/m$^3$
$w_{\text{plaster}}$ Weight of plaster kN/m$'$
$w_{L\text{L moment}}$ Weight of live load moment kN/m$^2$
$w_{D\text{L moment}}$ Weight of dead load moment kN/m$^2$
$w_{L\text{ shear}}$ Weight of live load shear kN/m$^2$
$w_{D\text{L shear}}$ Weight of dead load shear kN/m$^2$
$w_{U\text{moment}}$ Weight of ultimate moment kN/m$^2$
$w_{U\text{shear}}$ Weight of ultimate shear kN/m$^2$
$P_L$ Concentrated force left kN
$P_R$ Concentrated force right kN
$K_L$ Factor of moment left --
$K_R$ Factor of moment right --
$n_w$ Coefficient of effective width --
$B$ Beam width at compression side mm
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<td>Shear stress actual</td>
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\[ A_{\text{shrinkage}} \quad \text{Area of steel shrinkage} \quad \text{mm}^2 \]
\[ A_{\text{stirrup hangers}} \quad \text{Area of steel stirrup hangers} \quad \text{mm}^2 \]
\[ n_{\text{stirrups}} \quad \text{Number of stirrups} \quad -- \]
I. INTRODUCTION

A. Background

The construction industry is an industry with a unique anatomy. One of the largest industries worldwide, it cuts across various disciplines with many other industries depending on it. Despite the construction industry being an indicator for growth, it is a fragile industry that experiences cost overruns, time delays and conflicts among parties. Since projects are constrained by time, quality and cost, developers are more interested in a timely project completion with the required quality that yields the maximum return on investment. Fragmented into many specialties, intense competition, tight budget and less time, the industry proved to be a resilient one. Yet, many developers, project managers, structural engineers and architects are having over designed buildings (Deng & Poon, 2013). This may be attributed to the lack of innovation, resistance to new systems and technologies, little research and development, lack of skilled resources and shortage of intelligent systems to support project stakeholders.

In light of the recent advancements in systems integration in construction, affordable housing is in need of an optimization system that would yield higher mutual benefits for residents and developers. Having been considered one of the main items under the basic needs in Maslow’s hierarchy of needs, shelter or housing is an essential element in the physiological needs. Considered as a basic need, housing affordability poses an immense threat to developing countries advancement as well as developed countries continuity. It is an indisputable fact that the consequences of the lack of affordable housing are detrimental to societies. The hierarchy proposed by Maslow suggests that one would not properly function without the physical requirements for survival (Maslow, 1943). Thus, affordable housing should be the priority of governments to ensure the survival and prosperity of their nation.
B. Definition of affordable housing

There is no universal definition for affordable housing that is accepted in all countries. There are several efforts made to the term affordable housing. Some researchers defined affordable housing as the housing that median income residents may afford according to their country and region (Bhatta, 2010).

1. Australia

In Australia, affordable housing is defined as the housing that low or middle income households would be able to afford without affecting their ability to sustainably meet other basic needs. They further clarified that housing should have a reasonable location with an acceptable standard for residents. The target group is seen to be families or households with relative income equivalent to the bottom 60% in the household income distribution. It should be noted that the lowest group, bottom 20%, are usually renters or retirees who have already invested in the home many years ago. For households within the 20-60% income brackets, housing affordability declined. Some invest in a home while others rely on rental accommodation to be able to meet other living costs sustainably. Investments in housing for the rich, upper 60-80% and 80-100%, yields higher return. This encourages private investors and real estate developers to target the wealthy. Private investment for the wealthy is sufficient to meet the demand thus there is no government intervention in this sector. On the other hand, the demand for housing by low-income and middle-income households is not sufficiently met and thus the intervention of the government is a must to stimulate the affordable housing market (Australian Council of Trade Unions, 2007).

2. United States of America

The US department of Housing and Urban Development (HUD) considers affordable housing as the housing in which low or middle income households would be able to afford with no more than 30% of their income. A report by HUD identified the major barriers to affordable housing to be either within government control or beyond the government control. Factors affecting housing affordability are construction costs, development regulations, financing, lack of jobs and legal issues. Several initiatives have
been proposed for revamping regulations, offering simplified financing programs and long-term loans, availability of jobs in proximity and introducing new laws to help curb the need for affordable housing. The construction cost is composed of the land price, labor, equipment and materials costs. The cost of land is usually related to the regulatory rules that are in place and the governmental policies that regulate land prices. Affordable housing land prices are not usually correlated with the demand of housing. It is rather somehow subsidized by governments in an effort to assist low and middle income households acquire affordable homes (Georgia Department of Community Affairs, 2014).

3. Egypt

The Egyptian law defines low-income housing as housing that households earning 30,000 EGP or less per year can afford. The definition of affordable housing is as per the Egyptian law according to article 1 of Prime Minister Decree 1864 of year 2008 which is an update on article 35 of mortgage law 148 of year 2001. This definition is not accurate seeing that two-thirds of the Egyptian workforce are not formally employed with contracts and insurance. The current loan to income ratio that the government is offering for the social housing project is 35% which is a risk to households living at the upper poverty line. Furthermore, the definition of low-income housing being households with 30,000 EGP annual income includes the highest income quintile. Thus, higher social classes will be competing with lower social classes for the offered units. Housing prices and current income levels are not increasing proportionally. Rather, the housing prices are booming while income levels are relatively stagnant. The issues associated with housing in Egypt are rather related to governmental policies, regulations, unhealthy bureaucracies and lack of adequate housing (Egyptian Center for Economic & Social Rights, 2014).

C. Housing affordability index

Housing affordability index is simply a measure of affordability of housing. This index is introduced to properly value the relative affordability of housing units. For the United States, the National Association of Realtors publishes the monthly index and the method to calculate it along with other supplementary materials. An index of 100
signifies that a household earning a median income would be able to afford the house, where an index above 100 means that they will have more than enough funds for housing and less than 100 means that they will not have the enough funds for the home. Through the housing affordability index, governments may derive the income limits for loan eligible candidates or households, eligibility to mortgages and other financing programs (National Association of Realtors, 2014).

D. Problem statement

With the complexities and rapid advancement of the industry, there is a growing need for construction systems and models to solve complex problems. Through the development of models and systems, project parties would be better equipped to achieve project targets through meeting the budget, completing the project on time, improving quality and maximizing return. With the rise in investment in residential projects, one would expect many units to be available to accommodate the increasing demand for housing. Despite this high spending in real estate residential projects, fewer units are made available as developments are being directed towards luxurious properties for the wealthy. Looking at the brighter side, a boom in construction of residential projects would create immense opportunities for various trades and industries that depend on it. However, housing affordability is still a pressing matter that needs attention (Anuta, 2014).

It is evident that a boom in the construction industry would not mean higher affordable housing units, but rather luxurious units that are fewer in number (Anuta, 2014). This may be attributed to the fact that luxurious units yield a higher return on investment and the lack of support and incentives from the government for developers to invest in affordable housing. Proactive management approaches are under research to equip decision makers and project parties with the necessary tools to solve the shortage of housing units (Lafarge Egypt, 2010). Efforts have been made to minimize the cost of affordable housing through modular construction, prefabrication, economies of scale and low cost materials. Researchers covered most aspects related to affordable housing and structural optimization; however, no one integrated the size of units with the design optimization considering cost. Thus, there is a gap in the research of structural design
optimization of architectural layouts. Integrating the sizes of the units with optimization would mutually benefit developers and potential residents of affordable homes. With the increasing need for affordable housing and the scarcity of resources, government initiatives, new technologies, construction systems and models are forced to fulfill the need.

**E. Objective and scope**

Initially, this research set out to experiment the relationship between the variation in unit area and unit cost. Through this experiment, one would be able to derive an initial scatter graph as shown in Figure 1. Variations in the correlated data are not significant but will have an impact if multiple units were implemented or if the structural system of the building was selected or configured differently. The graph revealed potential for structural design optimization and its implementation to case study projects for validation. It indicated that the relation between cost and area is non-linear such that we are able to optimize the cost for a given area or increase the area for a given cost.

Through tackling the gap in the literature of affordable housing and design optimization, an optimization model is proposed to integrate the varying sizes of units with optimization. The proposed model is a customizable one that offers the flexibility to tailor the model based on respective house parameters, design code constraints and project constraints. This model will impact the construction industry thereby mutually benefiting developers and housing residents. The cost figures presented are based on the Egyptian construction market cost data and the design is based on the Egyptian Code of Practice ECP 2007 for design of reinforced concrete structures (Housing and Building National Research Center, 2007). The cost figures and design code constraints are tailored to be adjustable as per the user’s requirements and needs.

Figure 1 illustrates the relation between the reinforced concrete unit cost and the Gross Internal Unit Area (GIUA) that is referred to as the area measured to the internal face of the perimeter walls of the housing unit. It is evident that the cost of two units with identical areas may vary due to rounding reinforcing bars and/or concrete dimensions. Similarly, the area of two units with identical costs may vary for the same reasons. The figures of the reinforced concrete unit cost and GIUA and their relationship with one
another varies according to the cost data and defined constraints. Figure 1 is an illustration of random constraints for various layouts to signify the non-linearity of the relationship between reinforced concrete cost and GIUA.

![Gross Internal Unit Area vs. Reinforced Concrete Unit Cost](image)

Figure 1 Gross Internal Unit Area (GIUA) vs. Reinforced concrete cost

The model presented in this research exploits the variations in the cost versus area graph through various techniques as per the user defined variables and constraints. The cost indicated here is only covering the reinforced concrete floors, encompassing the beams and slabs, and is based on the Egyptian construction market cost data of January 2015. Available options are tailored to achieve the following objective:

- Optimize the reinforced concrete floor cost of housing units through varying the dimensions of the rooms

In addition to this objective, the thesis investigates the sensitivity of selected parameters on the model output. Through this objective, the model is able to optimize:

- Housing units within a specified budget to result in layouts with varying areas where the model would prefer the layout with the least cost per m2
• Housing units within a specified area range to result in layouts with varying cost where the model would prefer the layout with least cost per m2

The major features of the model are as follows:

• Customizable structural parameters, references and codes
• Production of Bill of Quantities for concrete and another for concrete and architectural finishing as per the user requirements
• User friendly input and output interfaces

The optimization of the architectural parametric variables with the respective goals, defined limits, parameters and constraints is based on the following concepts:

• Optimizing the architectural restrictions per room
• Unifying the area and applying optimization to achieve the lowest cost

F. Research methodology

In the research methodology section, an outline of the method of research is presented in the form of a flow chart. Figure 2 illustrates the sequence followed in this research starting with the literature review that encompass research of affordable housing models implemented worldwide, advanced construction and management techniques for optimizing cost and time, structural design optimization, design of reinforced concrete beams and slabs as per ECP 2007 and costs of labor and material of reinforced concrete works in the Egyptian market.
This research is organized into five chapters where each chapter builds on the previous one forming an integrated thesis as outlined below:

1. **Chapter I: Introduction**

   It introduces the thesis topic through outlining a review of background information about the topic. In addition, it discusses the definition of affordable housing with a focus on Australia, the United States of America and Egypt which have
appropriate definitions to this research. It presents the housing affordability index as a measure of affordability and its application. Further, it states the problem statement, objective and scope, research methodology and thesis organization.

2. Chapter II: Literature review

   It presents the literature review associated with research concerned with affordable housing models, advanced construction and management and optimization of design. It further signifies the gap in the literature review.

3. Chapter III: Model development

   It provides a process for the model development that involves the design methodology, different design approaches, and design of reinforced concrete beams and slabs as per ECP 2007. Further, the model integrates the sizes of the units with the design optimization using genetic algorithms and discusses the optimization results.

4. Chapter IV: Case study applications

   To validate the model, two case studies were considered, a low-income affordable house and the other is a middle income affordable house where the optimization results are presented along with a sensitivity analysis of one of the parameters.

5. Chapter V: Conclusion

   Summarizes the research findings, presents the limitations and offers recommendations for future research.
II. LITERATURE REVIEW

A. Introduction

Efforts have been made to minimize the cost of affordable housing through modular construction, prefabrication, economies of scale, low cost materials. The research and application of affordable housing varies in importance in different countries. With the rising trend towards luxurious residence, high-rise towers, gated communities, countries are facing shortage in affordable housing units. Several other initiatives have been introduced in an effort to tackle the shortage of affordable housing ranging from construction techniques, cost-reduction strategies, governmental policies and regulations to optimization and building information modeling integration. It is an indisputable fact that housing affordability is posing a massive threat to the economic stability and prosperity of nations.

Several researches were conducted in an effort to optimize the design of reinforced concrete structural elements considering various design constraints. The optimization of the design of structural elements was accelerated through the breakthroughs in the computing industry and programming. Optimization was initially based on computer programs and expert systems that sometimes follow a nonlinear approach to finding a solution. Researchers were concerned with minimizing the reinforcement in structural elements, quantifying the effect of steel cost on solutions and optimizing the cost of reinforced concrete structures. This prompted the advancement of research in structural design optimization of building elements considering various factors and codes. Research conducted revolves around the use of various optimization techniques to enhance the efficiency of the design of structural elements, some considering the structural constraints alone whereas others considering the various costs associated with the different designs.
B. Affordable housing models

1. Micro-apartment complex

Micro-apartment complexes are apartments that encompass creative design layouts of the different apartment rooms and facilities. It may often have shared services: toilets, kitchen and dining areas. This concept depends on efficient use of space as the apartments are relatively small. Smart designs have been incorporated to save space and make the apartment more practical.

2. Modular housing

Modular housing is housing modules that are manufactured in a factory and transported to the site as a finished product. This type of housing allows for economies of scale in the production and heavily depends on the fabrication of the house in a controlled environment resulting in a higher quality. Modular housing may accommodate several design layouts with all shapes and sizes. Through economies of scale and the efficiency of the controlled environment, this technique leads to massive savings.

3. Structural insulated panels

Similar to modular housing, structural insulated panels construction is another technique that substitutes the traditional construction of floors, walls and roofs. Through the use of the insulated panels, the building is energy efficient and structurally sound. This innovative approach is also manufactured in a controlled environment resulting in a higher quality. Unlike modular housing, it is assembled onsite which may lead to complications given the relatively new construction approach.

4. Modified mobile homes

Mobile homes are another housing initiative that is usually used as temporary housing. They are often implemented as permanent housing to become more affordable. Seeing that they are not appealing housing units to live in, initiatives have been introduced to upgrade the old ones thus conserving materials and cutting costs (Common Ground Affordable Housing Solutions, 2014).
C. Advanced construction and management

1. Housing proximity costs GIS modeling

Several other researches assessed the challenges to affordable housing projects. Such researches use Geographic Information System (GIS) models to locate and analyze employment-housing proximity relationships for residents. Proximity of work locations to the housing is vital in the development of communities and for drawing people towards living in these houses affordably. Housing target groups should be studied carefully to fully understand their needs and their proximity preferences. Through the use of GIS, researchers were able to use the multi-layered data to better understand the housing affordability crisis. Governments are advised to seek demographic information and results of social studies to properly assess the needs of communities in an effort to address them in a suitable manner. Expansion of the city should take into account new infrastructure networks as well as the creation of new job opportunities for residents of the housing complex to work in proximity to their homes. Several cost models were developed taking into account the infrastructure, neighborhood, driving cost and accessibility (US Department of Housing and Urban Development, 2013).

2. Sustainable construction cost reduction efforts

Some researchers with an environmental drive are seeking to transform the industry to a more sustainable one with their efforts to produce sustainable green buildings with lower costs and higher environmental returns and quality. While the integration of sustainability in construction is synonymous to higher costs, researchers were able to integrate it early on in the project to reduce its cost impact.

3. Lean construction in affordable housing

Other researchers examined the application of lean techniques in construction to further improve their impacts. Inspired from the industrial and manufacturing industries, lean construction would aim to decrease the waste produced while increasing the value of the products. They further investigated the application of the lessons learned from lean in the industry with a focus on the market of affordable housing. The benefits of lean in construction is massive with the budget controlling techniques, design and construction
schedule condensation, reduction in costs through early integrated planning with all parties and the consideration of facility operation costs of energy and maintenance. Researches in lean construction further investigated cost effectiveness of risk management seeing the various uncertainties in the industry. The implementation of risk management proved to be cost effective in reducing the impact of uncertainties, improving the confidence of time and cost predictions as well as operational costs that are not frequently considered. Novak suggests that an awareness of the benefits of lean in construction for affordable housing would aid project stakeholders to identify potential areas of savings and yield higher value to the project (Novak, 2014).

4. **Low income housing cost optimization using BIM**

Integrating Building Information Modeling with genetic algorithms is another effort in the research of affordable housing units where it utilizes the BIM technology coupled with a scheduling tool to determine the activities alternatives and propose solutions that achieve least cost and time while attaining the highest LEED points. The integration of BIM research is one based on Egypt in particular where it takes into account the struggles facing the Egyptian government. Decreasing the cost of the low income housing units is one of the major efforts that are considered in Egypt. This is due to the fact that Egypt’s population is increasing at an alarming rate with a decrease in the relative income. Thus, an intelligent model is presented where it supports parametric modeling as well as optimization (Marzouk & Metawie, 2014).

Marzouk and Metawie utilize BIM to present properties of materials, quantities, alternatives and the location of the project. It shows the benefit of integrating BIM in sustainable construction optimization where it may aid in analysis, modeling, building orientation, building massing and site management. BIM is not limited to the optimization of sustainable construction but may extend to 4D modeling where it would integrate the time as the 4th dimension with the 3D parametric model to be able to model the impact of changes on the time of the project. In addition, it further extends to 5D modeling where it would integrate the cost as the 5th dimension to the 4D model to be able to predict the impact of changes on the cost and time of the project. Marzouk and Metawie further utilize Genetic Algorithms (GA) optimization to model the quantities,
activities, materials data, LEED point calculations and schedule in an effort to reach a more optimized solution. (Marzouk & Metawie, 2014).

D. Optimization techniques

Elbeltagi et al. considers heuristics as a tool for optimization. It is simply an algorithm that simplifies the problem and provides near optimum solutions. They are typically implemented when precision is not the highest priority and the optimal solution would be exhaustive or difficult to find. Heuristic techniques encompass a number of evolutionary algorithms; genetic algorithms, memetic algorithms, particle swarm, ant colony, shuffled frog leaping and others (Elbeltagi et al., 2005).

Evolutionary algorithms evolve generations through development, growth, progression, advancement and improvement over time. They are iterative approaches to problem solving that mimic the social behavior and natural evolution of species. Complex optimization problems that traditional optimization methods fail to solve might be solved with the implementation of such algorithms (Hornby & Pollack, 2002).

Characterized by randomness, evolutionary algorithms randomly generate the population to find a near optimum solution. The population is a set of individual chromosomes that is composed of a set of genes where each gene represents a specific variable. Each individual chromosome represents a possible solution to the problem under study. Through the fitness function each individual chromosome in the population is assigned a measure of fitness relative to the other chromosomes or potential solutions. The fitness function is the quantitative information that guides the algorithm in its search for a solution. Several algorithms have been investigated through the literature to assess their relative efficiencies. Having reviewed the literature, genetic algorithms are the most suitable to optimize affordable housing layouts. Genetic algorithms are applied to search for possible solutions for the optimization of the design of affordable housing.

1. Genetic Algorithms (GAs)

Genetic algorithm (GA) is a search heuristic that mimics the natural biological evolution and social behavior of species through the survival of the fittest. This metaheuristic is used to generate useful solutions for optimization and search problems
by natural evolution, such as inheritance, mutation, selection, and crossover (F., et al. 2010). Solutions are chromosomes like any other in the randomly generated population. The initial population created is assumed to have random solution of equal probabilities to be near or far optimum. Each solution or chromosome is evaluated to determine its relative fitness. Chromosomes may also be represented in binary format as strings of 0s and 1s (Whitley, 1994).

**Population**

Each solution or chromosome is composed of variables or genes. The length of each chromosome is equivalent to the number of variables. The architectural and structural dimensional parameters constitute the genes of each chromosome. The genes are the variables in the problem that are varied randomly to generate different chromosomes. The chromosomes are the possible random solutions that are available to undergo evolution. Chromosomes in genetic algorithms follow the Darwinian evolution of the survival of the fittest where all species become fitter through natural selection and competition. Genetic algorithms are considered to be biologically inspired algorithms that follow a set of general procedures.

The randomly created chromosome population is evaluated through the fitness function to determine the relative fitness of each chromosome and apply the algorithm that would aspire to improve the initial population through crossover or mutation of the chromosomes. Through reproducing new chromosomes and inserting them in the population, it improves the population and moves towards finding a nearer to optimum solution (Melanie, 1996).

**Selection**

Genes are randomly selected to reproduce new chromosomes that are considered to be viable solutions to the problem in question.

**Crossover**

This involves the reproduction of new chromosomes from currently existing ones through crossing over information contained in their respective parents. The exchange of
information or selection of genes between parents is done randomly with bias towards selecting fitter parents for the crossover.

**Mutation**

Chromosomes that are deemed less likely to survive due to their low relative fitness may be mutated to a fitter function. In this process, the chromosomes’ genes are altered in an effort to reach fitter chromosomes. The mutation is only bias towards selecting fitter parents to mutate whereas the new value of the altered gene is randomly selected. Unlike crossover which resembles the reproduction in natural evolution, mutation is a sudden generation of a chromosome that rarely takes place similar to what happens naturally. Mutation is a complementary process to the crossover since it helps the algorithm avoid getting trapped in any local minimums. The local minimum is perceived as the solution whereas the global minimum is the near optimum one. The same applies for the local and global maximums.

**Reinsertion**

This is the process of inserting the newly created offspring into the population.

**E. Design optimization**

1. **RC structural elements cost optimization**

Past research on weight minimization should not be applied in the optimization of the design of reinforced concrete structures, but should rather include cost in the equation. An investigation of the separate structural elements optimization presents interesting results when costs are incorporated. Even though a minimization in the weight means lower costs, it does not necessarily mean near optimum solutions. Costs associated with the various concrete structural elements and systems are incorporated in the optimization for more accurate and efficient results. Further, it investigates the literature chronologically regarding the optimization of the cost of reinforced concrete structures. One may notice that a great majority of the literature is concerned with structural weight minimization. However, cost minimization would be more appropriate when dealing with reinforced concrete structures. In addition, the inclusion of all associated costs: concrete,
steel, formwork, labor, fabrication, placement and transportation would further enhance
the literature. It was further recommended to take into account uncertainties present in
loads and resistances (Sarma & Adeli, 1998).

2. Multi-story and multi-bay RC structures optimization

Guerra and Kiousis investigated the optimal sizing of structural elements in multi-
story and multi-bay reinforced concrete structures including the various costs associated
with the elements. It investigates an optimized design method over the typical design
method considering the design constraints and cost data for proper comparison. Several
structural approaches were investigated along with different alternative members.
Examining multi-story structures compared to single-story structures yielded similar
results proving that they are proportional to one another (Guerra & Kiousis, 2006).

3. Four heuristic methods for RC bridge frames optimization

Perea et al. discuss the integration of heuristic optimization in the design of
reinforced concrete bridge frames. They investigated the random walk and descent local
search heuristic methods and used the threshold accepting and simulated annealing
metaheuristic methods to reach a near optimum solution. The use of four different
optimization techniques included proper comparison of their relative efficiency.
Conclusions reached included the inefficiency of the random walk method, followed by
the descent local search and the simulated annealing. The threshold accepting algorithm
has been concluded to be the most efficient of the four methods (Perea et al., 2008).

4. Metaheuristic charged system search for RC optimization

Other optimization techniques were investigated to reach a near optimum design.
Through considering metaheuristic charged system search for the optimization of multi-
story three dimensional reinforced concrete structural elements, a nearer to optimum
solution is yet to be obtained. Sensitivity analysis is incorporated in the research to
investigate the effect of various spans and different cases of loading on the efficiency of
the results obtained. The larger the structure, the more time and higher number of
iterations is required to reach an acceptable near optimum solution. Further, the charged
system search and enhanced charged system search are considered to be among the
algorithms that are able to reach results efficiently in a lower number of iterations (Kaveh & Behnam, 2013).

**F. Gap in the literature**

With the current challenges facing the construction industry, an upgrade or change is inevitable for the stability of the industry. The industry is challenged beyond the current pressures of delivering projects within the time schedule, at the stipulated budget with the required quality. Environmental and social considerations in construction have been put into perspective by critics and researchers. Scarcity has been a concern with the rising cost of resources due to the shortage in their supply relative to the escalating demand. Despite such concern, the industry is struggling and lagging behind in achieving efficient reinforced concrete designs that would make better use of resources and mutually benefit developers and residents.

Reviewing the literature of affordable housing, there is an evident gap in optimizing the sizes of the units through parametric ranges. Further developing on the literature review, a model is proposed to optimize the design of affordable housing units for the mutual benefit of residents and developers in an attempt to fill the gap. Through exploiting the variations in the reinforced concrete cost versus gross internal unit area curve, one would be able to have layouts having the same area but with different costs. Likewise, there are layouts having the same cost but with different areas. Therefore, this offers decision makers, developers, investors and project stakeholders the ability to optimize based on their preferences. The proposed model would further enhance the link between architectural parametric design and structural design through the utilization of a range for each dimension. The range for each parametric dimension allows for more optimized results in an effort to reach near optimum solutions. Optimization offers users the ability to optimize their design based on architectural restrictions per room and result in a near optimum layout. In addition to allowing the user to optimize the design based on architectural restrictions per room, the user is able to unify the area and optimize based on a selected area resulting in a building with the same area at a lower cost. Through the utilization of the model, resulting designs would lead to the efficient use of resources.
Further, the model would result in a decrease in the reinforced concrete cost per m2 thus lowering the cost of units on developers and lowering the price of units on residents.
III. MODEL DEVELOPMENT

Model development is divided into six sections: model process, system architecture, design methodology, design of slabs, design of beams and optimization. Throughout the sections, the model is developed continuously where sections are integrated for the model to function. Section A: Model process is the theory behind the model where it explains the cycle the model follows to reach results. Section B: System architecture illustrates the four different modules incorporated in the model, their organization and integration. Such modules include: technical module, database module, structural design module and optimization module. Following the system architecture is Section C: Design methodology where it illustrates the selected design philosophy and the various loads. Through explaining the design philosophy, the limit state load resistance factored design approach is selected to be applied on the model. The different loads that impact our structures are also presented. Section D: Design of slabs presents the design procedures for the design of reinforced concrete slabs where it starts with the slab thickness, loads calculation, analysis and design. Likewise, Section E: Design of beams follows the same design methodology and presents similar design procedures for the design of reinforced concrete beams where it illustrates the concrete dimensions, loads calculation, analysis and design.

Having established the design concepts, optimization is integrated with the design of slabs and beams in Section F: Optimization. Genetic algorithms are clarified and illustrated through population, selection, crossover, mutation and reinsertion of chromosomes and their genes. Further, the proposed model is illustrated in the system architecture and the series of user interface input steps. Model output such as the Bill of Quantities, new proposed layout and optimization results are presented. Further, the output of the optimization trials is compared to signify that one may select units with greater area at the same cost per m². Likewise, one may select units at lower cost per m² with the same area.
A. Model process

The process presented involves the use of the Egyptian Code of Practice 2007 for the Design of Reinforced Concrete structures in the design methodology. The proposed model is a development of the traditional design method. In Figure 3, two approaches to the design of construction projects are presented. The traditional design method is one where the architectural design is completed, followed by the structural design where it is later sent to construction. A similar modified approach to this design model may involve the structural engineer proposing an adjustment to the architectural design where the design is sent back to the architectural designer to adjust and confirm the modified design. A new approach is presented in this thesis where the proposed design model introduces a cycle to this procedure. It starts with the architectural design where the architect defines a specific range of dimensions that is sent to the structural engineer with initial dimensions. The structural engineer would produce the structural design along with its cost. A new set of dimensions are proposed and sent back to the architectural designer within the specified range for a more optimized design. The design cycle continue until the least cost per m2 layout is reached. In this thesis, there will be defined stopping criteria that will stop the algorithm in an attempt to reach a suitable solution.

Figure 3 Model theory
Figure 4 illustrates the model process for the design methodology to calculate loads, internal forces, concrete dimensions, reinforcement and production of bill of quantities, along with its costs. Further, optimization continues the cycle where it keeps iterating the architectural parameters to achieve a more optimized reinforced concrete floor design. The process presented allows the model to be easily tailored to other markets with their design codes and cost calculations. In the case studies presented, costs are derived from present Egyptian construction market average rates of January 2015.

The proposed process gives the user the ability to input relevant cost data. This is to account for the apparent variation in the cost data from one user to the other. To facilitate the optimization, the user enters project data and relevant cost data to tailor the model to his respective project. An input interface is developed for the user to input general project data, technical data, architectural parametric limits and structural cost
data. Architectural cost data are included in the model capability to enable the user to optimize both structural and architectural aspects by altering the objective of the model to minimize the overall cost per m2 rather than the reinforced concrete cost only. Despite this capability, the results presented do not consider the architectural costs due to the high variation in their cost. Further, optimization would work through the trials altering the architectural parameters within the defined limits, thus altering the concrete dimensions, loads calculation, analysis, design, quantities, areas, costs and cost per m2.

Since there is a high variation in the cost of architectural finishing depending on the finishing, furniture, fittings and equipment, the model’s genetic algorithm processor focuses on the structural aspect of the design and does not consider the architectural aspect. Reviewing the reinforced concrete design limits available in the Egyptian Code of Practice 2007, massive savings may be achieved in the reinforced concrete floor cost (Housing and Building National Research Center, 2007). In the code, there are concrete and steel reinforcement limitations that the model utilizes to reach near optimum results. For steel reinforcement, limitations include:

- Maximum and minimum steel reinforcement specified for slabs and beams
- Specific commercially available steel bar diameters
- Minimum number of steel reinforcement bars
- Minimum spacing between steel reinforcement bars

Due to these limitations, there will be variations between the required area of steel and the selected one, minimum number of bars in beams and slabs that drives the model to optimize and achieve a larger dimension at a lower cost per m2. Likewise, for concrete, limitations include:

- Minimum dimensions of elements
- Specific increments of dimensions
- Unified dimensions for specific elements

Likewise, due to these limitations, there will be variations between required dimensions and selected ones. Such increments facilitate the optimization leaving room for near optimum results at lower costs and/or with larger area.
B. System architecture

The system architecture presented in Figure 5 is developed to illustrate how the system works. The model is composed of several modules: technical module, database module, structural design module and the optimization module. Each module has several processes implemented to help other modules achieve the required system output. The constituents of each module are outlined in the list below and the interaction between the processes is illustrated in Figure 5.

Technical module:

- Project data
- Technical data
- Architectural parameters

Database module:

- References database
- Structural cost data
- Architectural cost data
- Cost database

Structural module:

- Structural design module

Optimization module:

- Genetic algorithm processor
C. Design methodology

The design methodology detailed procedures is attached in Appendix I – Design Module that includes the equations and procedures for the design of slabs and design of beams.

1. Design philosophies

In design, there are several design philosophies one may follow that relate to adjusting loads and resistance. Limit state load resistance factored design approach is selected where the loads are magnified and the resistance is reduced. The resistance factors used for reducing resistance is usually higher for concrete than steel. Steel has a higher quality control as it is produced in a factory which is considered to be a controlled
environment. Concrete on the other hand has a lower quality control as it might be mixed on site which is considered to be an uncontrolled environment.

The design approach aims to design beams such that if failure occurs, it would happen in the steel first then the concrete as steel is a ductile material and concrete is a brittle material. As per the Egyptian Code of Practice 2007, the steel should fail first if excessive loading is to occur to allow for evacuation time. The Egyptian Code of Practice 2007 imposes ductile failure due to steel rather than premature failure due to concrete (Housing and Building National Research Center, 2007).

2. Loads

Design of structures is implemented against a number of loads to account for their impacts and ensure the resilience of the structure. Figure 6 illustrates the various kinds of loads that impact our structures.

**Gravity Loads**

These loads include dead load and live load. The dead load varies according to the loads imposed on the floor. It may consist of the following: own weight, flooring including sand, mortar, tiles, wood and marble, plastering of walls, isolation and
insulation materials, false ceiling and lights, decorative materials, permanent and temporary walls, Mechanical Electrical and Plumbing MEP systems, Heat Ventilation Air Conditioning HVAC and fire fighting. The unit weight of each item of the dead load is defined by the user. It may be tailored as per the user’s requirements in the model user interface.

The live load is not calculated, but is considered to be uniformly distributed over the area. It is obtained from the Egyptian Code of Practice 2007 for calculating loads on reinforced concrete and masonry structures as per the use of the building and function of the area (Housing and Building National Research Center, 2007). In the case of residential buildings, it usually takes into account the people moving loads, furniture and equipment.

\textit{Lateral Loads}

These loads include wind load and seismic earthquake load. They are usually critical in high rise buildings typically 4 stories and above for concrete structures and steel structures. Wind loads must always be considered in design of steel structures due to the light weight of such structures compared to concrete structures; however, earthquake loads may only govern in high rise buildings and/or structures supporting heavy loads such as tanks, silos, and factories with heavy machinery.

\textit{Other Loads}

Settlement and temperature loads are other loads that impact the building. They are loads that do not affect determinate structures. They only affect indeterminate structures.

\textbf{D. Design of slabs}

The design of slabs follows the Egyptian Code of Practice for Design of Reinforced Concrete structures 2007 procedures outlined in Design of slabs under Appendix I – Design Module.
1. **Slab thickness**

As per the Egyptian Code limitation, slab thickness cannot be less than 8cm. It is first categorized as one-way slab or two-way slab according to the aspect ratio defined in the Code. Slab thickness is calculated using the shorter slab dimension as it is the main direction transferring the loads. Slab thickness is selected to be multiples of 20mm or 50mm as per practical requirements. No deflection checks were required as the slab thickness was obtained as per the Egyptian Code of Practice 2007 recommended equations that include the effect of long and short term deflections (Housing and Building National Research Center, 2007).

2. **Loads calculation**

The dead load and live load are calculated separately. The dead load is the own weight of the slab in addition to the flooring load. The flooring load may comprise of the flooring finish cover, plastering, isolation and insulation materials, false ceiling and lights, decorative materials and MEP fixtures. The live load is not calculated but rather selected from the Code according to the purpose of the building or function of the area.

Upon determining the loads for two-way slabs, they are distributed according to the load distribution layout in a trapezoidal and triangular distribution with coefficients $\beta$ and $\alpha$ in longer and shorter direction respectively. The load distribution is a factor of the aspect ratio multiplied by the ratios $m_1$ and $m_2$ of the length between inflection points and the effective span. Following the distribution of the loads, ultimate loads calculated and used to determine the ultimate moments. For one-way slabs, the ultimate weight of slab is applied in the shorter direction without distribution. In addition to the mid span and mid support moment calculations, the Egyptian Code assumes there is a moment at the end supports equivalent to $\frac{wt^2}{24}$ for fixation provisions where $w$ denotes the distributed load and $l$ denotes the length. Since the live load constitutes approximately 40% of the weight of the structure and will not have a significant impact, no cases of loading were considered and it is assumed that the live load is applied on all slabs simultaneously.
3. Analysis

Calculated loads are analyzed to compute sagging and hogging moments in slabs. There are two methods used in the analysis of the moment, the code coefficient and the French equation. The code coefficient is easier to apply and is valid for 2 spans and more than 2 spans with a set of limitations. Despite the ease of application of the code coefficient, it may not accommodate variation in neighboring spans greater than 20%, variation in neighboring loads greater than 20%, concentrated loads and cantilevers. Such limitations tend to elect the French equation. With these limitations in the code coefficient method, the French equation would be a more suitable option for a more universal calculation where these limitations are no longer an obstacle for the ultimate moment calculations.

4. Design

The design of one way and two-way slabs follows the typical slab design procedure of determining the effective length, selecting the appropriate concrete cover and calculating the effective depth. As the shear force has to be resisted by the concrete, the ultimate shear is calculated from the shear forces obtained through the analysis. Ultimate shear stresses are computed and checked against the reduced shear capacity of concrete. If it exceeds such limit, the slab thickness would be increased until shear strength limit state is satisfied. Once satisfied, the calculated sagging and hogging ultimate moments were used to compute required bottom and top reinforcement. The design of one-way and two-way slabs is the same apart from the computation of the secondary area of steel in the one-way slab where in the two-way slab the main reinforcement is calculated in both directions.

E. Design of beams

The design of beams follows the Egyptian Code of Practice for Design of Reinforced Concrete structures 2007 procedures outlined in Design of beams under Appendix I – Design Module.
1. **Concrete dimensions**

As per the Egyptian Code and construction practice, beam depth cannot be less than three times the slab thickness and not greater than the difference between the floor height and recommended door height including the flooring finish. The different slab configurations influence the calculated beam depth through a factor for each configuration. Beam depth is unified throughout the building for ease of construction. No deflection checks for beams as long as the beam depth was obtained according to the Egyptian Code of Practice 2007 recommended equations that account for short and long term deflections. The beam depth is selected to be multiples of 50mm as per practical requirements. The beam width, however, is selected similar to the thickness of wall partitions (Housing and Building National Research Center, 2007).

2. **Loads calculation**

Similar to the calculations of the slab load, the dead load and live load are calculated separately. The dead load is the own weight of the beam, weight of wall and the weight of the slab dead load. The flooring load may comprise of the flooring finish cover, plastering, isolation and insulation materials, false ceiling and lights, decorative materials and MEP fixtures. The live load is not calculated but rather selected from the Egyptian Code of Practice 2007 according to the purpose of the building or function of the area.

According to the load distribution layout, the load is distributed in a trapezoidal and triangular distribution with coefficients $\beta$ and $\alpha$ as per the aspect ratio of slabs supported by beams. Following the distribution of the loads, ultimate loads of moment and shear are calculated. Equivalent loads are developed for ease of calculation for the weight of the dead load and live load for moment and shear. In addition to the mid span and mid support moment calculations, the Egyptian Code assumes there is a moment at the end supports equivalent to $\frac{wL^2}{24}$ for fixation provisions. Since the live load constitutes no more than 30% of the weight of the structure and will not have a significant impact, no cases of loading were considered and it is assumed that the live load is applied on all spans simultaneously.
3. Analysis

Similar to the analysis of slabs, calculated loads are used to analyze moment and shear in beams. There are two methods used in the analysis, the code coefficient and the French equation. The code coefficient is easier to apply and is valid for 2 spans and more than 2 spans with a set of limitations. Despite the ease of application of the code coefficient, it may not accommodate variation in neighboring spans greater than 20%, variation in neighboring loads greater than 20%, concentrated loads and cantilevers. Such limitations tend to elect the French equation. With these limitations in the code coefficient method, the French equation would be a more suitable option for a more universal calculation where these limitations are no longer an obstacle for the ultimate moment and shear calculations. In beam design, the shear force is resisted by the stirrups as there is a minimum requirement for shear reinforcement for beams. Unlike slabs which may not carry concentrated loads, beams are designed such that they may carry a concentrated load, such as carrying another beam.

4. Design

The design of sagging and hogging beam sections follow the typical beam design procedure of determining the concrete cover, calculating the effective depth, and effective width B for positive moment sections and area of steel reinforcing bars. The width is dependent on the type of section through a set of equations. The types of sections are T-section where the beam is in between two spans and the other is the L-section in the case of an edge beam which is basically reflecting the shape of compression zone in the beam and slab. For positive moment beams, the depth of compression side of beam is assumed not to exceed the slab thickness where the moment capacity of the section is calculated. The area of reinforcement is calculated by equating the resultant tension to the resultant compression caused by the moment. All the parameters of the reinforcing bars including; number of bars, diameter of bars and weight of reinforcement bars are calculated according to the required area of reinforcement required. The design procedure of hogging moment is identical to sagging except that the shape of the compression zone is rectangular such that the effective width of the beam equals to its actual width.
Several checks are incorporated in the design procedure to avoid exceeding the limits of the reinforcement ratio. Calculations of the minimum reinforcement ratio ensures that tensile stresses due to shrinkage are supported whereas calculations of the maximum reinforcement ensures ductile failure due to steel tension rather than brittle failure due to crushing of concrete. It should be noted that the least allowable spacing between bars is typically 25mm. Having the reinforcement ratio exceed the maximum, increase the depth of the section or add compression steel. Design of compression steel is very similar to normal beam section design where the additional moment required is calculated by the difference between the ultimate moment and the maximum section capacity (Housing and Building National Research Center, 2007). Compression steel is not considered as the range of spans is not large.

Unlike slabs, beams are designed to resist shear. The design of shear reinforcement follows the procedure of calculating the ultimate shear force, shear stress, maximum shear stresses and comparing the obtained stresses with the maximum. The applied shear stresses should not exceed the maximum stipulated by the Egyptian Code of Practice 2007. Otherwise, the section dimensions, depth or width, should be increased. Once the applied shear stresses satisfied the maximum, the amount of shear reinforcement or stirrups should be determined to support the excess shear stresses over the capacity of the concrete section. If no shear reinforcement is required, the minimum shear reinforcement is used. The design of shear provides number of branches, diameter and number of stirrups assuming specific yield strength for stirrups and ties. Beam shrinkage bars and stirrup hangers are calculated as percentages of the main steel reinforcement with a minimum requirement as per the Egyptian Code of Practice 2007. The number of rows of shrinkage bars is determined by the depth of the section. There are tensile stresses due to shrinkage that takes place when water evaporates. Stirrups are also added to the section to ensure that concrete in compression works with steel in tension to resist shear stresses (Housing and Building National Research Center, 2007).

The typical construction process for the reinforced concrete section is as follows: formwork preparation, placement of steel hangers typically Ø10, placement of main reinforcement, placement of stirrups, pouring of concrete, curing the floor for at least 14
days and removing the formwork after hardening of concrete according to spans between columns. According to the above discussions and illustrations, the design is an iterative process thus requires several checks to ensure that limits are not exceeded and the design is safe and economic. The model developed accommodates for several iterations to ensure safety of the structure and resilience of the model.

F. Optimization

Optimization is a set of techniques for solving complex problems through defining an objective function, identifying the constraints and setting the variables. Optimization is implemented through various techniques; linear programming, nonlinear programming, integer programming, dynamic programming, combinatorial optimization, heuristics and other techniques. Some of the optimization techniques are traditional methods that yield optimum solutions, whereas others are non-traditional that yield near optimum or approximate solutions.

1. Genetic Algorithms (GAs)

Figure 7 shows the development of the genetic algorithm population. Chromosomes are formed from the genes where the number of chromosomes indicates the population size n. The chromosomes are potential random solutions to the algorithm. The figure further clarifies the definition of each gene where the first 3 genes represent the x-dimensions of the house and the last 3 genes represent the y-dimensions of the house. Having genes as the dimensions, the chromosome is the combination of 6 genes with certain fitness. The fitness function in this genetic algorithm has an objective to minimize the cost per m2 that evaluates the fitness of each chromosome.
**Population**

<table>
<thead>
<tr>
<th>Chromosome 1</th>
<th>250</th>
<th>200</th>
<th>150</th>
<th>300</th>
<th>100</th>
<th>150</th>
<th>404.93</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromosome 2</td>
<td>250</td>
<td>180</td>
<td>150</td>
<td>450</td>
<td>100</td>
<td>200</td>
<td>406.98</td>
</tr>
</tbody>
</table>

**Selection**

Figure 8 shows two parent chromosomes that are selected for reproduction, known as cross over where each parent would exchange specific genes to the child randomly. Exchanging dimensions would yield a different chromosome with a new fitness evaluation.

<table>
<thead>
<tr>
<th>Parent 1</th>
<th>250</th>
<th>200</th>
<th>150</th>
<th>300</th>
<th>100</th>
<th>150</th>
<th>404.93</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parent 2</td>
<td>250</td>
<td>180</td>
<td>150</td>
<td>450</td>
<td>100</td>
<td>200</td>
<td>406.98</td>
</tr>
</tbody>
</table>

The selection in the genetic algorithms follows the survival of the fittest theme.
There are several points of crossover according to the number of lines of crossover. Figure 9 shows the one point crossover and Figure 10 shows two point crossovers of 2 parents and their respective offspring. The points of crossovers are selected randomly where the different chromosomes exchange dimensions at one point.

### One point crossover

<table>
<thead>
<tr>
<th>Parent 1</th>
<th>250</th>
<th>200</th>
<th>150</th>
<th>300</th>
<th>100</th>
<th>150</th>
<th>404.93</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parent 2</td>
<td>250</td>
<td>180</td>
<td>150</td>
<td>450</td>
<td>100</td>
<td>200</td>
<td>406.98</td>
</tr>
</tbody>
</table>

### Generate random crossover range

<table>
<thead>
<tr>
<th>Offspring 1</th>
<th>250</th>
<th>200</th>
<th>150</th>
<th>450</th>
<th>100</th>
<th>200</th>
<th>403.47</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offspring 2</td>
<td>250</td>
<td>180</td>
<td>150</td>
<td>300</td>
<td>100</td>
<td>150</td>
<td>411.05</td>
</tr>
</tbody>
</table>

In this example, offspring 1 has a better fitness value than its parents. Thus, it’s more likely to survive and get involved in future crossovers. Whereas offspring 2 is less fit and is less likely to survive.
Similar to the one point cross over, offspring 2 is fitter than its parents. Thus, it’s more likely to survive and get involved in future crossovers. Whereas offspring 1 is less fit and is less likely to survive.

**Mutation**

Unlike crossover which lets the offspring inherit the characteristics or genes of his parents, mutation involves the alteration in the genes of the chromosomes randomly to result in a new chromosome with altered genes. Figure 11 illustrates the reason behind the inclusion of mutation. Cases where solutions may keep optimizing towards achieving a local minimum or maximum rather than towards the global solution are a good example for mutation to impact the optimization. Mutation in this case will alter the population randomly in an attempt to reach an optimized solution and avoid getting trapped in a local minimum or maximum.
Reinsertion

This is the process of inserting the newly created offspring into the population.

2. Model

The proposed optimization model is developed in Microsoft Office Excel 2007 and is run on Windows 7, 32-bit Operating System, Intel Core 2 Duo CPU 1.40GHz 4.00GB. The genetic algorithm optimization tool utilized is a Microsoft Excel add-in, Evolver TM V.5.5 developed by Palisade Corporation. The optimization is typically based on the following:

- Number of genes (Variables) = 6 genes
- Number of chromosomes (Initial population) = 50 chromosomes
- Crossover rate = 0.5
- Mutation rate = 0.1
- Stopping criteria = 5000 trials
- Running time = 50 minutes

Through trials and research, the above values are suitable for this optimization problem where a population of 50, cross over rate of 0.5 and mutation rate of 0.1 give good results.

User interface

The user interface in this research is developed such that users would be able to tailor the program or model to their project needs. Data entered in the model include project data, technical data, architectural parameters, structural elements cost data and

Figure 11 Local and global minimum and maximum
architectural elements cost data. Furthermore, the nature of the model ensures the uniqueness of each project through the variations in the specifications and tailored data input for the model. The user interface offers users the ability to customize the model based on their cost data, project location, workmanship, commercially available materials and equipment, various code limitations, designer requirements and other data as appropriate. In step 1, the user would input the basic project data which constitutes the project type, project name, employer name, contractor name, engineer name and a brief project description, as shown in Table 1.

<table>
<thead>
<tr>
<th>Ref</th>
<th>Item</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Project type</td>
<td>Affordable housing</td>
</tr>
<tr>
<td>2</td>
<td>Project Name</td>
<td>National youth housing development 2020</td>
</tr>
<tr>
<td>3</td>
<td>The Employer</td>
<td>ABC Properties Egypt S.A.E.</td>
</tr>
<tr>
<td>4</td>
<td>The Contractor</td>
<td>XYZ</td>
</tr>
<tr>
<td>5</td>
<td>The Engineer</td>
<td>DEF</td>
</tr>
<tr>
<td>6</td>
<td>Project description</td>
<td>Affordable housing development of generic units for youth</td>
</tr>
</tbody>
</table>

In step 2, the user would then input the project technical data as per project specifications and design conditions. As indicated in Table 2, users enter fixed data that is unique to their project. Input includes fixed dimensional parameters such as the floor height, door dimensions, window dimensions and flooring height. In addition, the user would input material and loads technical data: specific gravity of concrete, type of wall used, reduction factors as per code, beam width, other dead load and live load information. The model offers users the ability to input various dead loads: flooring cover, plastering, isolation and insulation, false ceiling and lights, decorative materials and MEP fixtures. Steel information is then entered including the type of steel used, minimum diameter of stirrups, stirrup hangers and shrinkage bars, yielding strength of stirrup bars, reinforcement bars and concrete strength.
As shown in Table 3, the user would input the architectural dimensional parameters that are considered variables in the design. The model offers users the ability to input a range rather than a specific dimension to allow the optimization processor to work within this range. The user would input the minimum and maximum dimensional parameters for each dimension as specified.

As shown in Table 3, the user would input the architectural dimensional parameters that are considered variables in the design. The model offers users the ability to input a range rather than a specific dimension to allow the optimization processor to work within this range. The user would input the minimum and maximum dimensional parameters for each dimension as specified.

<table>
<thead>
<tr>
<th>Ref</th>
<th>Item</th>
<th>Value</th>
<th>Units</th>
<th>Height</th>
<th>Units</th>
<th>Width</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Floor height m</td>
<td>3.1 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>External door 1</td>
<td>1 number</td>
<td>2.2 m</td>
<td>1 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Internal door 4</td>
<td>4 number</td>
<td>2.2 m</td>
<td>1 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Window to living 1</td>
<td>1 number</td>
<td>1.2 m</td>
<td>1.4 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Window to bedrooms 2</td>
<td>2 number</td>
<td>1.2 m</td>
<td>1.4 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Window to toilet 1</td>
<td>1 number</td>
<td>0.8 m</td>
<td>0.6 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Window to kitchen 1</td>
<td>1 number</td>
<td>1 m</td>
<td>1.2 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Flooring height</td>
<td>0.1 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Width of column 0.25 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>$Y_{\text{concrete}}$</td>
<td>25 kN/m$^3$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>$Y_c$</td>
<td>1.5 --</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>$Y_s$</td>
<td>1.15 --</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Type of wall</td>
<td>Red brick</td>
<td>--</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>External beam width 0.25 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Internal beam width 0.12 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>$Y_{\text{wall}}$</td>
<td>15 kN/m$^3$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>$Y_{\text{plaster}}$</td>
<td>22 kN/m$^2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Flooring cover</td>
<td>2 kN/m$^2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Plastering</td>
<td>0.5 kN/m$^2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Isolation and insulation</td>
<td>0 kN/m$^2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>False ceiling and lights</td>
<td>0 kN/m$^2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Decorative materials</td>
<td>0 kN/m$^2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>MEP fixtures</td>
<td>0 kN/m$^2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Live load</td>
<td>2 kN/m$^2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Steel for rebars 400/600 Mild</td>
<td>--</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>Steel for stirrups</td>
<td>Mild</td>
<td>--</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Ø stirrups</td>
<td>8 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>Ø stirrup hangers</td>
<td>10 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>Ø shrinkage bars</td>
<td>12 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>$F_{\text{yield stirrups}}$</td>
<td>240 N/mm$^2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>$F_{\text{cu}}$</td>
<td>25 N/mm$^2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>$F_{\text{yield rebars}}$</td>
<td>360 N/mm$^2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As shown in Table 3, the user would input the architectural dimensional parameters that are considered variables in the design. The model offers users the ability to input a range rather than a specific dimension to allow the optimization processor to work within this range. The user would input the minimum and maximum dimensional parameters for each dimension as specified.
Figure 12 illustrates the initial layout entered in the model where the configuration is presented and labeled in this layout based on the data entered in Table 3.

![Floor layout](image)

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
<th>Minimum dim (cm)</th>
<th>Dimension (cm)</th>
<th>Maximum dim (cm)</th>
<th>Minimum dim (m)</th>
<th>Dimension (m)</th>
<th>Maximum dim (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rooms X-dimension</td>
<td>295.00</td>
<td>450.00</td>
<td>450.00</td>
<td>2.95</td>
<td>4.50</td>
<td>4.50</td>
</tr>
<tr>
<td>2</td>
<td>Bathroom X-dimension</td>
<td>145.00</td>
<td>146.00</td>
<td>220.00</td>
<td>1.45</td>
<td>1.46</td>
<td>2.20</td>
</tr>
<tr>
<td>3</td>
<td>Kitchen X-dimension</td>
<td>195.00</td>
<td>243.00</td>
<td>300.00</td>
<td>1.95</td>
<td>2.43</td>
<td>3.00</td>
</tr>
<tr>
<td>4</td>
<td>Bedroom 1, Dining &amp; Living Y-dimension</td>
<td>295.00</td>
<td>295.00</td>
<td>450.00</td>
<td>2.95</td>
<td>2.95</td>
<td>4.50</td>
</tr>
<tr>
<td>5</td>
<td>Foyer Y-dimension</td>
<td>150.00</td>
<td>171.00</td>
<td>230.00</td>
<td>1.50</td>
<td>1.71</td>
<td>2.30</td>
</tr>
<tr>
<td>6</td>
<td>Bathroom Y-dimension</td>
<td>145.00</td>
<td>220.00</td>
<td>220.00</td>
<td>1.45</td>
<td>2.20</td>
<td>2.20</td>
</tr>
</tbody>
</table>

Followed by the project data, technical data and architectural dimensional parameters, the cost data is entered to form the optimization goal for the model. Table 5 indicate the structural cost data entered for the cast in-situ concrete for beams, reinforcement for beams and shuttering for beams and cast in-situ concrete for slabs,
reinforcement for slabs and shuttering for slabs according to the user input. Costs for the various items are obtained based on the Egyptian construction market data of January 2015. Reinforcement cost data is dependent on the steel with yielding strength 360 N/mm² where this cost includes the works associated with 1 kg of steel. Shuttering cost data is representative of the current market where it includes the works associated with the formwork. Concrete cost data on the other hand is rather dependent on the strength of the concrete where the Egyptian market has data for concrete with compressive strength 25, 30, 35 and 40 MPa which are commercially available. Concrete cost data is presented in Table 4 where it illustrates the corresponding cost per m³ of concrete for the required compressive strength.

Cost data is dependent on the method of construction and the overall scale of the project. The cost data presented in the thesis is based on the Egyptian construction market costs of January 2015. Further, the cost data applied to this thesis is based on structures composed of 400-600m² floor areas with 4 or more apartments per floor. The data presented is inclusive of material, labor, equipment and supervision costs. However, the user may choose to adjust the figures and include what is fit for the project.

<table>
<thead>
<tr>
<th>$F_{cu}$ (N/mm²)</th>
<th>Cost/m³ LE</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>600</td>
</tr>
<tr>
<td>30</td>
<td>630</td>
</tr>
<tr>
<td>35</td>
<td>660</td>
</tr>
<tr>
<td>40</td>
<td>705</td>
</tr>
</tbody>
</table>

### Table 4 Concrete cost data for various strength as of January 2015

### Table 5 User interface: project structural cost data

<table>
<thead>
<tr>
<th>Ref</th>
<th>Item</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Reinforced poured concrete beams</td>
<td>600</td>
<td>LE/m³</td>
</tr>
<tr>
<td>2</td>
<td>Reinforcement to poured concrete beams</td>
<td>7</td>
<td>LE/kg</td>
</tr>
<tr>
<td>3</td>
<td>Shuttering for beams</td>
<td>100</td>
<td>LE/m²</td>
</tr>
<tr>
<td>4</td>
<td>Reinforced poured concrete slabs</td>
<td>600</td>
<td>LE/m³</td>
</tr>
<tr>
<td>5</td>
<td>Reinforcement to poured concrete slabs</td>
<td>7</td>
<td>LE/kg</td>
</tr>
<tr>
<td>6</td>
<td>Shuttering for slabs</td>
<td>100</td>
<td>LE/m²</td>
</tr>
</tbody>
</table>

Despite the fact that optimization of the structural elements is the focus, architectural elements are calculated to have a feeling of the proportion of the cost in comparison to the structural elements cost. The User interface cost data for masonry,
doors and windows, plastering to walls and ceilings, paint to wall and ceilings, different flooring finishes are presented in Table 6. The finishing includes the building external for one floor. The proportion of the structural costs from the overall costs is dependent on the cost data input by the user. Table 7 presents the Gross Internal Unit Area (GIUA), reinforced concrete cost per m², reinforced concrete cost as well as the overall cost per m² and estimated cost. The percentage of the reinforced concrete cost to the overall cost is 33.30% for this initial layout presented. This thesis aims to optimize the reinforced concrete cost per m², thus it only concentrates on this percentage. Although this percentage is not fixed, it will revolve around this range for our model. For residential projects, the normal range of the reinforced concrete cost to overall cost is 30%, where it decreases for luxurious properties to 20% or less and increases for affordable housing to reach 40% or more according to the input cost data.

Table 6 User interface: project architectural cost data

<table>
<thead>
<tr>
<th>Ref</th>
<th>Item</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Internal walls</td>
<td>80</td>
<td>LE/m²</td>
</tr>
<tr>
<td>2</td>
<td>External walls</td>
<td>640</td>
<td>LE/m²</td>
</tr>
<tr>
<td>3</td>
<td>1000mm x 2200mm internal wooden door</td>
<td>1000</td>
<td>LE/nr</td>
</tr>
<tr>
<td>4</td>
<td>1000mm x 2200mm external wooden door</td>
<td>2000</td>
<td>LE/nr</td>
</tr>
<tr>
<td>5</td>
<td>1400mm x 1200mm window to living &amp; dining</td>
<td>1700</td>
<td>LE/nr</td>
</tr>
<tr>
<td>6</td>
<td>1400mm x 1200mm window to bedrooms</td>
<td>1550</td>
<td>LE/nr</td>
</tr>
<tr>
<td>7</td>
<td>600mm x 800mm window to toilet</td>
<td>310</td>
<td>LE/nr</td>
</tr>
<tr>
<td>8</td>
<td>1200mm x 1000mm window to kitchen</td>
<td>1200</td>
<td>LE/nr</td>
</tr>
<tr>
<td>9</td>
<td>Plaster to internal walls</td>
<td>40</td>
<td>LE/m²</td>
</tr>
<tr>
<td>10</td>
<td>Plaster to ceiling</td>
<td>50</td>
<td>LE/m²</td>
</tr>
<tr>
<td>11</td>
<td>Paint to internal walls</td>
<td>45</td>
<td>LE/m²</td>
</tr>
<tr>
<td>12</td>
<td>Wall finish to toilets</td>
<td>100</td>
<td>LE/m²</td>
</tr>
<tr>
<td>13</td>
<td>Paint to ceiling</td>
<td>45</td>
<td>LE/m²</td>
</tr>
<tr>
<td>14</td>
<td>Flooring to bedrooms</td>
<td>100</td>
<td>LE/m²</td>
</tr>
<tr>
<td>15</td>
<td>Flooring to foyer and living and dining area</td>
<td>100</td>
<td>LE/m²</td>
</tr>
<tr>
<td>16</td>
<td>Flooring to toilets</td>
<td>100</td>
<td>LE/m²</td>
</tr>
<tr>
<td>17</td>
<td>Flooring to kitchen</td>
<td>100</td>
<td>LE/m²</td>
</tr>
<tr>
<td>18</td>
<td>Plaster to kitchen</td>
<td>60</td>
<td>LE/m²</td>
</tr>
<tr>
<td>19</td>
<td>Paint to external walls</td>
<td>50</td>
<td>LE/m²</td>
</tr>
</tbody>
</table>
The project Bill of Quantities is generated for each layout. Table 8 presents the concrete Bill of Quantities for the unit floor of the initial project data. An architectural Bill of Quantity is optional should the user select to include.
### Table 8 Model input: Concrete Bill of Quantities

<table>
<thead>
<tr>
<th>Ref</th>
<th>Item Description</th>
<th>Qty</th>
<th>Unit</th>
<th>Rate (EGP)</th>
<th>Total (EGP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Superstructure</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>Cast-in situ concrete</td>
<td>6.75</td>
<td>m³</td>
<td>600.00</td>
<td>4050.63</td>
</tr>
<tr>
<td>B</td>
<td>To beams</td>
<td>6.96</td>
<td>m³</td>
<td>600.00</td>
<td>4174.25</td>
</tr>
<tr>
<td>C</td>
<td>Reinforcement</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>To slabs</td>
<td>671.28</td>
<td>kg</td>
<td>7.00</td>
<td>4698.95</td>
</tr>
<tr>
<td>E</td>
<td>Shuttering</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>To soffits of slabs</td>
<td>691.93</td>
<td>kg</td>
<td>7.00</td>
<td>4843.52</td>
</tr>
<tr>
<td>E</td>
<td>To sides and soffits of beams</td>
<td>77.73</td>
<td>m²</td>
<td>100.00</td>
<td>7773.39</td>
</tr>
<tr>
<td>F</td>
<td>To soffits of slabs</td>
<td>51.44</td>
<td>m²</td>
<td>100.00</td>
<td>5144.20</td>
</tr>
</tbody>
</table>

| Carried to Summary | 30684.95 |

### 3. Optimization results

The optimization runs in the Evolver TM 5.5 Excel add-in aiming to generate a near optimum solution through a number of iterative trials. Through the various trials, the solution attempts to converge to the near optimum solution. The proposed model is
implemented on 30,000 trials to further study the results relatively based on the following:

- Number of genes (Variables) = 6 genes
- Number of chromosomes (Initial population) = 50 chromosomes
- Crossover rate = 0.5
- Mutation rate = 0.1
- Stopping criteria = 30,000 trials

This is illustrated through the Evolver watcher, output progress steps, gross internal unit area versus reinforced concrete cost per m2 scatter graph, gross internal unit area versus reinforced concrete cost scatter graph and sensitivity charts.

**Evolver watcher**

The Evolver TM 5.5 optimization watcher shows a close-up graph focusing on the last 2000 trials and another presenting all trials. The convergence of the solution based on defined constraints along the iterations is illustrated in both graphs. In an attempt to reach a near optimum solution, Figure 13 gives an indication of the progression of the model. The convergence process and progress steps are further shown on the evolver watcher graphs as presented in Table 9.

![Evolver Watcher](image)

**Figure 13 Evolver TM 5.5 sample optimization screenshot**
**Progress steps**

Table 9 presents a sample of the progress steps that outline the progress in the iterative process to achieve the objective and reach the least cost per m². Progress steps present the successful iterations that yielded lower or nearer to optimum cost per m² than previous iterations. It further shows the calculations of the Gross Internal Unit Area GIUA where it equates to area measured from the internal face of the perimeter walls. In the sample model presented, it equates to the multiplication of the effective lengths from the inside of the external walls of each direction. In the cost/area column, the value decreases with the jump in trials where each recorded progress step signifies a near to optimum solution. The total cost is calculated as the multiplication of the cost per m² by the Gross Internal Unit Area.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Elapsed Time</th>
<th>Cost/area (LE/m²)</th>
<th>X-dim Adjustable Cells</th>
<th>Y-dim Adjustable Cells</th>
<th>GIUA (m²)</th>
<th>Cost (LE)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>X1</td>
<td>X2</td>
<td>X3</td>
<td>X-dim</td>
</tr>
<tr>
<td>1</td>
<td>0:00:01</td>
<td>565.18</td>
<td>450.00</td>
<td>146.00</td>
<td>243.00</td>
<td>814.00</td>
</tr>
<tr>
<td>2</td>
<td>0:00:02</td>
<td>537.18</td>
<td>406.00</td>
<td>155.00</td>
<td>243.00</td>
<td>779.00</td>
</tr>
<tr>
<td>3</td>
<td>0:00:03</td>
<td>529.64</td>
<td>450.00</td>
<td>146.00</td>
<td>204.00</td>
<td>775.00</td>
</tr>
<tr>
<td>8</td>
<td>0:00:04</td>
<td>524.34</td>
<td>450.00</td>
<td>146.00</td>
<td>232.00</td>
<td>803.00</td>
</tr>
<tr>
<td>32</td>
<td>0:00:12</td>
<td>524.08</td>
<td>450.00</td>
<td>146.00</td>
<td>233.00</td>
<td>804.00</td>
</tr>
<tr>
<td>40</td>
<td>0:00:14</td>
<td>508.53</td>
<td>450.00</td>
<td>146.00</td>
<td>231.00</td>
<td>802.00</td>
</tr>
<tr>
<td>56</td>
<td>0:00:20</td>
<td>495.27</td>
<td>450.00</td>
<td>155.00</td>
<td>243.00</td>
<td>823.00</td>
</tr>
<tr>
<td>140</td>
<td>0:00:46</td>
<td>495.14</td>
<td>450.00</td>
<td>155.00</td>
<td>243.00</td>
<td>823.00</td>
</tr>
<tr>
<td>184</td>
<td>0:01:00</td>
<td>495.03</td>
<td>450.00</td>
<td>155.00</td>
<td>243.00</td>
<td>823.00</td>
</tr>
<tr>
<td>257</td>
<td>0:01:24</td>
<td>494.71</td>
<td>450.00</td>
<td>145.00</td>
<td>240.00</td>
<td>810.00</td>
</tr>
<tr>
<td>260</td>
<td>0:01:25</td>
<td>493.82</td>
<td>450.00</td>
<td>145.00</td>
<td>248.00</td>
<td>818.00</td>
</tr>
<tr>
<td>558</td>
<td>0:03:02</td>
<td>493.59</td>
<td>450.00</td>
<td>145.00</td>
<td>255.00</td>
<td>825.00</td>
</tr>
<tr>
<td>602</td>
<td>0:03:16</td>
<td>493.24</td>
<td>450.00</td>
<td>145.00</td>
<td>258.00</td>
<td>828.00</td>
</tr>
<tr>
<td>630</td>
<td>0:03:25</td>
<td>493.06</td>
<td>450.00</td>
<td>145.00</td>
<td>258.00</td>
<td>828.00</td>
</tr>
</tbody>
</table>

**Model Output**

The output interface restates the project data for presentation purposes along with the Gross Internal Unit Area (GIUA), reinforced concrete cost per m², reinforced concrete cost as well as the overall cost per m² and estimated cost as shown in Figure 10.
Floor layout is another output for graphical representation of the output model that is shown in Figure 14. It illustrates the layout, dimensions, locations and overall structure.

<table>
<thead>
<tr>
<th>Project data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project type</td>
</tr>
<tr>
<td>Project name</td>
</tr>
<tr>
<td>The Employer</td>
</tr>
<tr>
<td>The Contractor</td>
</tr>
<tr>
<td>The Engineer</td>
</tr>
<tr>
<td>GIUA</td>
</tr>
<tr>
<td>Reinforced concrete cost per m²</td>
</tr>
<tr>
<td>Estimated reinforced concrete cost</td>
</tr>
<tr>
<td>RC and finishing cost per m²</td>
</tr>
<tr>
<td>Estimated RC and finishing cost</td>
</tr>
<tr>
<td>Project description</td>
</tr>
</tbody>
</table>

The project Bill of Quantities is part of the output. Table 11 presents the concrete Bill of Quantities for the unit floor. The model also includes an architectural finishing works Bill of Quantity that may be added to the output of the model as per the user requirements.
### Table 11 Model output: Concrete Bill of Quantities

<table>
<thead>
<tr>
<th>Ref</th>
<th>Item Description</th>
<th>Qty</th>
<th>Unit</th>
<th>Rate (EGP)</th>
<th>Total (EGP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>CONCRETE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Superstructure</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cast-instu concrete</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>To beams</td>
<td>6.55</td>
<td>m³</td>
<td>600.00</td>
<td>3929.98</td>
</tr>
<tr>
<td>B</td>
<td>To slabs</td>
<td>8.71</td>
<td>m³</td>
<td>600.00</td>
<td>5228.72</td>
</tr>
<tr>
<td></td>
<td>Reinforcement</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>To beams</td>
<td>592.18</td>
<td>kg</td>
<td>7.00</td>
<td>4145.25</td>
</tr>
<tr>
<td>D</td>
<td>To slabs</td>
<td>762.83</td>
<td>kg</td>
<td>7.00</td>
<td>5339.81</td>
</tr>
<tr>
<td></td>
<td>Shuttering</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>To sides and soffits of beams</td>
<td>76.45</td>
<td>m²</td>
<td>100.00</td>
<td>7645.46</td>
</tr>
<tr>
<td>F</td>
<td>To soffits of slabs</td>
<td>63.71</td>
<td>m²</td>
<td>100.00</td>
<td>6371.34</td>
</tr>
<tr>
<td></td>
<td><strong>Carried to Summary</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>32660.56</strong></td>
</tr>
</tbody>
</table>

**Gross internal unit area vs. reinforced concrete cost**

This graph illustrates the relationship between the gross internal unit area and the reinforced concrete cost. The graph presented in Figure 15 is for 30,000 trials run on the layout of Figure 14. The graph presented shows the correlation and signifies the multiple

48
values of concrete unit cost for the same unit area. Likewise, it indicates the multiple areas for the same concrete unit cost. Results are clustered in Figure 15 as well for the same reasons as for Figure 16. Results are clustered into groups to illustrate the jumps between various layouts where there might be a shift in the design due to maximum and minimum steel reinforcement specified for slabs and beams, specific commercially available steel bar diameters, minimum number of steel reinforcement bars, minimum spacing between steel reinforcement bars. Thus, there will be variations between the required area of steel and the selected one, the minimum number of required steel bars in beams and slabs that drives the model to optimize and achieve a larger dimension at a lower cost per m². Likewise, for concrete, there are: minimum dimensions of elements, specific increments of dimensions and unified dimensions for specific elements

![Figure 15 Gross internal unit area vs. reinforced concrete cost](image)

**Gross internal unit area vs. reinforced concrete cost per m²**

This graph illustrates the relationship between the gross internal unit area and the reinforced concrete cost per m². The graph presented in Figure 16 is for 30,000 trials run
on the layout of Figure 14 based on defined constraints. The graph presented shows the correlation and signifies the multiple values of reinforced concrete cost per m² for the same area with a difference in the layout. Likewise, it indicates the multiple areas for the same reinforced concrete cost per m² with a difference in the layout. The correlation in the figure presented indicates that as the area of the floor increases, the cost per m² of the floor decreases up until the lowest point on the graph where the cost per m² increases with an increase in the area.

One may notice that the point with the lowest cost per m² is the near optimum solution that the model would give. Figure 16 shows the lowest point to be approximately at 66.24m² with 493.06LE/m² as the approximate cost per m². This graph further illustrates that one may select units with greater area at the same cost per m². If 520 LE/m² is selected as the cost per m², one may select units 51m² or 72m² with a variation in layout. Further, one may select units with lower cost per m² with the same area. For example, one may select units with 501LE/m² or 591LE/m² for an area of 65m² with a variation in layout. This is considered to be a saving of circa 15% of the reinforced concrete cost. The saving is massive; however, it largely depends on the original layout, dimensional parameters and the model constraints that the user defines. The above are just examples; however, the saving may be more or may be less depending on the user input.

Results are clustered into groups to illustrate the jumps between various layouts where there might be a shift in the design due to maximum and minimum steel reinforcement specified for slabs and beams, specific commercially available steel bar diameters, minimum number of steel reinforcement bars and minimum spacing between steel reinforcement bars. Thus, there will be variations between the required area of steel and the selected one, minimum number of bars in beams and slabs that drives the model to optimize and achieve a larger dimension at a lower cost per m². Likewise, for concrete, limitations include minimum dimensions of elements, specific increments of dimensions and unified dimensions for specific elements.
Figure 16 Gross internal unit area vs. reinforced concrete cost per m²
**Architectural layout representation of several layouts**

The architectural layout representations are developed using Autodesk Revit 2015. The model provides an illustration of the effect of the different layouts on the reinforced concrete cost per m². All layouts are of the same relative proportion demonstrating the variation in appearance with a change in the dimensional parameters. Illustrations of layouts are in the plan view including the horizontal and vertical dimensional parameters.

One may select units with lower cost per m² for the same area. For example, for an area of 65m², one may select units with 591LE/m² as per Figure 17 layout or 501LE/m² as per Figure 18 layout. This is considered to be a saving of circa 15% of the reinforced concrete cost. Table 12 further demonstrates the calculations that derive such conclusions. A youth development project is presented as an example where it is made up of 100 buildings each composed of 5 floors with 4 flats per floor resulting in a total of 2000 flats. Comparing layout B to layout A, one may achieve a saving of 15.04% equivalent to 11,550,360 LE with a slight increase in area of 0.22% if the 2000 flats project is considered. Similarly, comparing layout E to layout A, one may achieve a saving of 14.97% equivalent to 11,496,720 LE with an increase in area of 1.88% if the 2000 flats project is considered. The savings in cost and increase in area achieved signify the advantage of implementing optimization in the design of reinforced concrete floors.

<table>
<thead>
<tr>
<th>Table 12 Comparison of various architectural layouts A, B and E</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Steel (kg)</strong></td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Concrete (m³)</strong></td>
</tr>
<tr>
<td><strong>Shuttering (m²)</strong></td>
</tr>
<tr>
<td><strong>GIUA (m²)</strong></td>
</tr>
<tr>
<td><strong>RC cost (LE)</strong></td>
</tr>
<tr>
<td><strong>RC cost per m² (LE/m²)</strong></td>
</tr>
<tr>
<td><strong>RC cost of 2000 units (LE)</strong></td>
</tr>
<tr>
<td><strong>Potential savings (LE)</strong></td>
</tr>
<tr>
<td><strong>% Decrease in Cost</strong></td>
</tr>
<tr>
<td><strong>% Increase in Area</strong></td>
</tr>
</tbody>
</table>
Figure 17 Layout A: Plan view of layout with Area=65m² and Cost/m²=591LE/m²

Figure 18 Layout B: Plan view of layout with Area=65m² and Cost/m²=501LE/m²
Likewise, one may select units with greater area at the same cost per m2. If 520 LE/m2 is selected as the cost per m2, one may select units 51m2 as per Figure 20 layout or 72m2 as per Figure 19 layout. This is considered to be a saving of circa 28.42% of the reinforced concrete cost with a proportional decrease in area of 28.39%. The proportionality between cost and area does not signify any savings for this case. Table 13 further demonstrates the calculations that derive such conclusions. A youth development project is presented as an example where it is made up of 100 buildings each composed of 5 floors with 4 flats per floor resulting in a total of 2000 flats. Comparing layout D to layout C, one may achieve a saving of 28.42% equivalent to 21,158,660 LE with a proportional decrease in area of 28.39% if the 2000 flats project is considered. This is not considered an effective shift in design. However, this is considered finding as one may reduce the size of the unit with a proportional decrease in the cost. Whereas, comparing layout E to layout C, we find that we may achieve a saving of 12.27% equivalent to 9,133,040 LE with a decrease in area of 7.46% if we consider the 2000 flats project. The significant savings in cost achieved with the slight decrease in area signify the advantage of implementing optimization in the design of reinforced concrete floors.

<table>
<thead>
<tr>
<th></th>
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<th>Layout D</th>
<th>Layout E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel (kg)</td>
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<td>1,108.30</td>
<td>1,355.01</td>
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<tr>
<td>Concrete (m3)</td>
<td>17.40</td>
<td>12.01</td>
<td>15.26</td>
</tr>
<tr>
<td>Shuttering (m2)</td>
<td>154.80</td>
<td>116.84</td>
<td>140.17</td>
</tr>
<tr>
<td>GIUA (m2)</td>
<td>71.58</td>
<td>51.26</td>
<td>66.24</td>
</tr>
<tr>
<td>RC cost (LE)</td>
<td>37,227.08</td>
<td>26,647.75</td>
<td>32,660.56</td>
</tr>
<tr>
<td>RC cost per m2 (LE/m2)</td>
<td>520.11</td>
<td>519.81</td>
<td>493.06</td>
</tr>
<tr>
<td>RC cost of 2000 units (LE)</td>
<td>74,454,160</td>
<td>53,295,500</td>
<td>65,321,120</td>
</tr>
<tr>
<td>Potential savings (LE)</td>
<td>---</td>
<td>21,158,660</td>
<td>9,133,040</td>
</tr>
<tr>
<td>% Decrease in Cost</td>
<td>---</td>
<td>28.42</td>
<td>12.27</td>
</tr>
<tr>
<td>% Decrease in Area</td>
<td>---</td>
<td>28.39</td>
<td>7.46</td>
</tr>
</tbody>
</table>
Figure 19 Layout C: Plan view of layout with Area=72m² and Cost/m²=520LE/m²

Figure 20 Layout D: Plan view of layout with Area=51m² and Cost/m²=520LE/m²
The result of the optimization is illustrated in Figure 21 showing the lowest point to be approximately at an area of 66.24m² with a reinforced concrete cost per m² equivalent to 493.06LE/m².

![Figure 21 Layout E: Plan view of layout with Area=66.24m² and Cost/m²=493.06LE/m²](image)

Through the variation in layout, one may notice that for larger rooms, the model favors the room to be a square rather than rectangle such that the load from slabs is equally distributed on all sides. However, if the aspect ratio increases, the majority of the load will be transferred in the short direction that will increase the concrete dimensions and reinforcement of the supporting beams thus leading to an increased cost.

4. **Sensitivity**

The results of the optimization are dependent on the defined parameters in the User interface. For example, varying the steel strength or the concrete strength would yield different results. Seeing that the cost data presented is based on the Egyptian construction market data where steel is only commercially manufactured with yielding
strength $F_{\text{yield}}$ 360 N/mm$^2$, the sensitivity of the yielding strength of the steel is not investigated. The sensitivity of the reinforcement steel may however be investigated in other countries based on the available steel specifications and their respective cost data.

Concrete strength sensitivity analysis is investigated to assess the impact of the variation in the concrete strength on the cost per m$^2$ and the reinforced concrete cost. It illustrates the effect of the concrete strength on the objective function of the algorithm. Through varying the concrete strength, the reinforced concrete cost per m$^2$ changes altering the reinforced concrete cost of the layout. The sensitivity analysis for this would be specific for each project and not universal for future projects. However, there is a trend that may be indicative and useful in future projects. Sensitivity analysis is investigated on Case I: Low-income affordable house and Case II: Middle-income affordable house and presented in the next chapter under IV. Case study applications.
IV. CASE STUDY APPLICATIONS

Two case studies were studied to investigate the efficiency and sensitivity of the model to various layouts. Both case studies are targeting the design of an affordable house with an objective function aiming to minimize the cost per m². Through applying the presented model to various designs and layout, it may be concluded that the model achieves the required objective and assists in the design of affordable houses.

A. Case I: Low-income affordable house

Affordable houses are usually associated with low-income houses. However, both terms are not synonymous to one another. Affordable housing concepts may be applied to various types of homes for various target groups. Case I is a low income affordable house consisting of 2 bedrooms, living and dining area, kitchen, toilet and a foyer for circulation purposes. The area of the model varies approximately from 35m² up to 83m² as per the architectural dimensional constraints defined. The layout is run on the developed model with an objective to minimize the reinforced concrete cost per m². The optimization is based on the following:

- Number of genes (Variables) = 6 genes
- Number of chromosomes (Initial population) = 50 chromosomes
- Crossover rate = 0.5
- Mutation rate = 0.1
- Stopping criteria = 5000 trials
- Running time = 50 minutes

1. Layout

Figure 22 illustrates the layout where the integration of the sizes of the units with optimization to reach a near optimum cost per m² is investigated.
2. **Evolver watcher**

Evolver watcher is utilized to have a visual representation of the convergence of the solution with respect to the number of trials and time. The Evolver TM 5.5 optimization watcher shows the convergence of the solution along the iterations with a close-up graph focusing on the last 500 trials and another presenting all trials. Figure 23 gives an indication of the progression of the model in an attempt to reach a near optimum solution. It further shows the convergence process and the progress steps.
This illustrates the massive drop at the beginning of the optimization that signifies a decrease in the reinforced concrete cost per m². It also shows the original value of the objective and the best value obtained. As the iterative process continues and trials are made, the solution converges in an effort to reach a lower cost per m².

3. **Optimization results**

Case I initial constraints, code limitations, user architectural parametric ranges and specified limits are placed for the model to optimize and reach a nearer to optimum solution for the layout. In this model, the user further specified that beams should have no more than 6 steel bars for external beams and 4 steel bars for internal beams. The initial dimensions of the layout are input for the model to present the initial design before optimization. Figure 24 shows the initial layout for Case I before optimization. Based on this layout, the model designed the structural elements which are illustrated in Figure 25 and Table 14. Figure 25 shows the structural system configuration, reinforced concrete slab thickness, steel reinforcement for slabs, and reinforced concrete beam dimensions. Table 14 presents the steel reinforcement details for beams comprising of top, bottom and stirrups reinforcement. The sample design drawing before and after optimization is under Appendix II – Case I sample design drawing.

![Image](image.png)

*Figure 24 Initial layout for Case I before optimization*
Figure 25 Initial design for Case I initial layout before optimization

Table 14 Beam reinforcement details for Case I initial layout before optimization

<table>
<thead>
<tr>
<th>Type</th>
<th>1st span</th>
<th>2nd span</th>
<th>Details</th>
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</thead>
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<td>2016</td>
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<td>2</td>
<td>2012</td>
<td>3#16</td>
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<tr>
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<td>2016</td>
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<td>7</td>
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</tr>
<tr>
<td>8</td>
<td>2012</td>
<td>2012</td>
<td>2012</td>
</tr>
</tbody>
</table>

61
The model is then run, where the optimization engine starts optimizing the initial layout presented in Figure 24 to achieve a layout with a lower cost per m2. The final layout for Case I after optimization is illustrated in Figure 26. Based on this layout, the model designed the final structural elements which are illustrated in Figure 27 and Table 15. Figure 27 shows the structural system configuration, reinforced concrete slab thickness, steel reinforcement for slabs, and reinforced concrete beam dimensions. Table 14 presents the steel reinforcement details for beams comprising of top, bottom and stirrups reinforcement.

![Low-Income Affordable Housing Layout](image)

**Figure 26 Final layout for Case I after optimization**
Figure 27 Final design for Case I final layout after optimization

Table 15 Beam reinforcement details for Case I final layout after optimization

<table>
<thead>
<tr>
<th>Type</th>
<th>1st Story</th>
<th>2nd Story</th>
<th>Storage</th>
</tr>
</thead>
<tbody>
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<td>Left</td>
<td>Mid</td>
<td>Right</td>
</tr>
<tr>
<td>1c</td>
<td>Top</td>
<td>5d10</td>
<td>2010</td>
</tr>
<tr>
<td></td>
<td>Bottom</td>
<td>5d10</td>
<td></td>
</tr>
<tr>
<td>2c</td>
<td>Top</td>
<td>4d10</td>
<td>2010</td>
</tr>
<tr>
<td></td>
<td>Bottom</td>
<td>2d18</td>
<td></td>
</tr>
<tr>
<td>3c</td>
<td>Top</td>
<td>5d10</td>
<td>2010</td>
</tr>
<tr>
<td></td>
<td>Bottom</td>
<td>5d10</td>
<td></td>
</tr>
<tr>
<td>4c</td>
<td>Top</td>
<td>5d10</td>
<td>2010</td>
</tr>
<tr>
<td></td>
<td>Bottom</td>
<td>6d12</td>
<td></td>
</tr>
<tr>
<td>5c</td>
<td>Top</td>
<td>4d10</td>
<td>2010</td>
</tr>
<tr>
<td></td>
<td>Bottom</td>
<td>2d18</td>
<td></td>
</tr>
<tr>
<td>6c</td>
<td>Top</td>
<td>5d10</td>
<td>2010</td>
</tr>
<tr>
<td></td>
<td>Bottom</td>
<td>5d10</td>
<td></td>
</tr>
<tr>
<td>9d</td>
<td>Top</td>
<td>2d12</td>
<td>2010</td>
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<tr>
<td></td>
<td>Bottom</td>
<td>2d18</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>Top</td>
<td>2d12</td>
<td>2010</td>
</tr>
<tr>
<td></td>
<td>Bottom</td>
<td>2012</td>
<td></td>
</tr>
</tbody>
</table>
Based on the constraints set and the initial layout of Case I, Table 16 presents the quantities of steel reinforcement, concrete, shuttering, as well as the GIUA, RC cost, RC cost per m2 to compare between the two layouts. A youth development project is presented as an example where it is made up of 100 buildings each composed of 5 floors with 4 flats per floor resulting in a total of 2000 flats. Comparing the final layout to initial layout, one would find that an increase in cost of 13.83% equivalent to 7,935,860LE with a significant increase in area of 30.50% if we consider the 2000 flats project. The increase in cost coupled with the massive increase in area achieved signifies the advantage of implementing optimization in the design of reinforced concrete floors.

<table>
<thead>
<tr>
<th>Component</th>
<th>Initial</th>
<th>Final</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel (kg)</td>
<td>1,214.83</td>
<td>1,355.01</td>
</tr>
<tr>
<td>Concrete (m3)</td>
<td>13.28</td>
<td>15.26</td>
</tr>
<tr>
<td>Shuttering (m2)</td>
<td>122.22</td>
<td>140.17</td>
</tr>
<tr>
<td>GIUA (m2)</td>
<td>50.76</td>
<td>66.24</td>
</tr>
<tr>
<td>RC cost (LE)</td>
<td>28,692.63</td>
<td>32,660.56</td>
</tr>
<tr>
<td>RC cost per m2 (LE/m2)</td>
<td>565.23</td>
<td>493.06</td>
</tr>
<tr>
<td>RC cost of 2000 units (LE)</td>
<td>57,385,260</td>
<td>65,321,120</td>
</tr>
<tr>
<td>Increase in cost (LE)</td>
<td>---</td>
<td>7,935,860</td>
</tr>
<tr>
<td>% Increase in Cost</td>
<td>---</td>
<td>13.83</td>
</tr>
<tr>
<td>% Increase in Area</td>
<td>---</td>
<td>30.50</td>
</tr>
</tbody>
</table>

B. Sensitivity analysis on Case I

1. Sensitivity analysis of concrete strength on optimization

   The sensitivity of the concrete strength is investigated on the optimization model. Concrete strength is varied with all other variables constant to properly investigate its effect. It is varied with values 25, 30, 35 and 40 MPa. The overall and individual effect of the sensitivity of the concrete strength is examined on the reinforced concrete cost per m2, gross internal unit area and reinforced concrete cost. The data presented is the limits of each parameter and is plotted on the sensitivity charts for clarity and comparison.

   **Sensitivity of concrete strength on cost per m2**

   Table 17 presents the sensitivity of varying the concrete strength on the cost per m2. The lowest cost per m2 and highest cost per m2 are presented to indicate the range
achieved. The limits of the cost per m$^2$ are useful in presenting the limitations of optimizing at this specific strength with the specified constraints. The lowest cost per m$^2$ achieved for Case I: Low-income affordable house is 471.32 LE/m$^2$ at a concrete strength of 35MPa. This is dependent on the layout configuration.

### Table 17 Sensitivity of concrete strength on cost per m$^2$ of case study I

<table>
<thead>
<tr>
<th>Concrete strength (MPa)</th>
<th>Lowest Cost/area (LE/m$^2$)</th>
<th>Highest Cost/area (LE/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1  25MPa Fy360</td>
<td>493.06</td>
<td>631.01</td>
</tr>
<tr>
<td>2  30MPa Fy360</td>
<td>476.46</td>
<td>666.59</td>
</tr>
<tr>
<td>3  35MPa Fy360</td>
<td>471.32</td>
<td>610.98</td>
</tr>
<tr>
<td>4  40MPa Fy360</td>
<td>476.42</td>
<td>611.08</td>
</tr>
</tbody>
</table>

Figure 28 illustrates the sensitivity of varying the concrete strength on the cost per m$^2$ in a graphical format. One may notice the trend in the lower end of the range of the cost per m$^2$. It is visible that increasing the concrete strength would yield a nearer to optimum solution as compared to lower concrete strength. However, the decrease between 30MPa and 35MPa and increase between 35MPa and 40MPa are not significant. The increase beyond the 35MPa is due to the effect of concrete strength on the moment of resistance of the section.
Sensitivity of concrete strength on reinforced concrete cost

Table 18 presents the sensitivity of varying the concrete strength on the reinforced concrete cost. The lowest reinforced concrete cost and highest reinforced concrete cost are presented to indicate the range achieved in optimizing for the least cost per m². The limits of the reinforced concrete cost are useful in presenting the limits achieved by the various trials.

Table 18 Sensitivity of concrete strength on reinforced concrete cost of case study I

<table>
<thead>
<tr>
<th>Concrete strength (MPa)</th>
<th>Lowest Cost (LE)</th>
<th>Highest Cost (LE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 25MPa Fy360</td>
<td>22,449.15</td>
<td>49,857.39</td>
</tr>
<tr>
<td>2 30MPa Fy360</td>
<td>22,027.21</td>
<td>45,078.28</td>
</tr>
<tr>
<td>3 35MPa Fy360</td>
<td>20,843.46</td>
<td>42,079.55</td>
</tr>
<tr>
<td>4 40MPa Fy360</td>
<td>20,052.16</td>
<td>44,978.16</td>
</tr>
</tbody>
</table>

Figure 29 illustrates the sensitivity of varying the concrete strength on the reinforced concrete cost in a graphical format. One may notice the trend in the lower end of the range of the reinforced concrete cost. It is visible that increasing the concrete
strength would yield a lower reinforced concrete cost as compared to lower concrete strength. However, at 30MPa, the lowest reinforced concrete cost is slightly lower than at 35MPa which shows that one may sacrifice the lowest cost per m2 presented in Figure 28 for the lowest reinforced concrete cost or vice versa. This usually depends on the budget allotted by the user.

![Sensitivity chart of concrete strength on reinforced concrete cost](image)

*Figure 29 Sensitivity of concrete strength on reinforced concrete cost of case study I*

**Sensitivity of concrete strength on gross internal unit area**

Table 19 presents the sensitivity of varying the concrete strength on the Gross Internal Unit Area GIUA. The lowest GIUA and highest GIUA are presented to indicate the range achieved in optimizing for the least cost per m2. The limits of the GIUA are useful in presenting the areas considered in this sensitivity analysis.
Table 19 Sensitivity of concrete strength on gross internal unit area of case study I

<table>
<thead>
<tr>
<th>Concrete strength (MPa)</th>
<th>Lowest GIUA (m²)</th>
<th>Highest GIUA (m²)</th>
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<tbody>
<tr>
<td>1 25MPa Fy360</td>
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<td>2 30MPa Fy360</td>
<td>39.49</td>
<td>73.46</td>
</tr>
<tr>
<td>3 35MPa Fy360</td>
<td>38.38</td>
<td>76.13</td>
</tr>
<tr>
<td>4 40MPa Fy360</td>
<td>36.00</td>
<td>79.94</td>
</tr>
</tbody>
</table>

Figure 30 illustrates the sensitivity of varying the concrete strength on the GIUA in a graphical format. One may notice the trend in the lower end of the range of the GIUA where increasing the concrete strength would yield a nearer to optimum solution as compared to lower concrete strength. In addition, the range of areas at corresponding concrete strength is varied to signify the near optimum areas that the model considered.

2. **Optimization output for sensitivity analysis of concrete strength**

Figure 31, Figure 33, Figure 35 and Figure 37 illustrate the relationship between the gross internal unit area and the reinforced concrete cost per m². The graphs presented
in the figures are for 5,000 trials run on the layout of Figure 22. The graph presented shows the correlation and signifies the multiple values of reinforced concrete cost per m2 for the same area with the variation in layout. Likewise, they indicate multiple areas for the same reinforced concrete cost per m2 for different layouts. The correlation in the figure presented indicates that as the area of the floor increases, a decrease in the cost per m2 of the floor is witnessed up until the lowest point on the graph where the cost per m2 increases with an increase in the area. One may notice that the point with the lowest cost per m2 is the near optimum solution that the model would achieve. The lowest point, the correlation of the graph, intensity of points and their distribution differ with varying the concrete strength as presented in the graphs. Results are clustered into groups that are correlated on a regression curve illustrating the relationship between the reinforced concrete cost per m2 and the GIUA. Regression curves are roughly plotted on the graphs to illustrate the correlation present. The regression curves indicate that the relationship is non-linear.

Followed by the graphs of the GIUA vs. reinforced concrete cost per m2, graphs of the GIUA vs. reinforced concrete cost are presented. Figure 32, Figure 34, Figure 36 and Figure 38 illustrate the relationship between the GIUA and the reinforced concrete cost. The graphs presented are for 5,000 trials run on the layout of Figure 22. The graph presented shows the correlation and signifies the multiple values of concrete unit cost for the same unit area. Likewise, it indicates the multiple areas for the same reinforced concrete cost. The regression lines of the clustered results illustrate the relationship between the reinforced concrete cost per m2 and the GIUA. Regression lines are roughly plotted on the graphs to illustrate the correlation present. The regression lines indicate that the relationship is linear.

The graphs further show a couple of clustered outliers that are not consistent with the regression or the trend of the graph. This may be the result of an inefficient design that significantly increases the reinforced concrete cost per m2. The clustering of points into groups illustrates the jumps between various layouts on both graphs where there might be shift in the design due to maximum and minimum steel reinforcement specified for slabs and beams, specific commercially available steel bar diameters, minimum
number of steel reinforcement bars and minimum spacing between steel reinforcement bars. Thus, there will be variations between the required area of steel and the selected one, minimum required number of steel reinforcement bars in beams and slabs that drives the model to optimize and achieve a larger dimension at a lower cost per m2. Likewise, for concrete, there are minimum dimensions of elements, specific increments of dimensions and unified dimensions for specific elements.
Optimization output for $F_{cu} = 25$ MPa

**Figure 31** Gross internal unit area vs. reinforced concrete cost per m$^2$ for $F_{cu} = 25$ MPa for case study I

**Figure 32** Gross internal unit area vs. reinforced concrete cost for $F_{cu} = 25$ MPa for case study I
**Optimization output for \( F_{cu} = 30 \text{ MPa} \)**

![Graph](image)

**Figure 33** Gross internal unit area vs. reinforced concrete cost per m\(^2\) for \( F_{cu} = 30 \text{ MPa} \) for case study I

![Graph](image)

**Figure 34** Gross internal unit area vs. reinforced concrete cost for \( F_{cu} = 30 \text{ MPa} \) for case study I
Optimization output for $F_{cu} = 35$ MPa

**Figure 35** Gross internal unit area vs. reinforced concrete cost per m$^2$ for $F_{cu} = 35$ MPa for case study I

**Figure 36** Gross internal unit area vs. reinforced concrete cost for $F_{cu} = 35$ MPa for case study I

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Optimization output for $F_{cu} = 40$ MPa

Figure 37 Gross internal unit area vs. reinforced concrete cost per m2 for $F_{cu} = 40$ MPa for case study I

Figure 38 Gross internal unit area vs. reinforced concrete cost for $F_{cu} = 40$ MPa for case study I
C. Case II: Middle-income affordable house

Despite the fact that affordable houses are usually associated with low-income houses, the concepts may be applied to multiple target groups and designs. Case II is a middle income affordable house consisting of 3 bedrooms, living and dining area, entrance, kitchen, toilet and a foyer for circulation purposes. The area of the model varies approximately from 74m2 to 218m2 as per the defined architectural dimensional constraints. The layout is run on the model with an objective to minimize the cost per m2. The optimization is typically based on the following:

- Number of genes (Variables) = 6 genes
- Number of chromosomes (Initial population) = 50 chromosomes
- Crossover rate = 0.5
- Mutation rate = 0.1
- Stopping criteria = 5000 trials
- Running time = 50 minutes

1. Layout

Figure 39 illustrates the layout of the middle income affordable house where the sizes of the units are integrated with optimization to reach a near optimum cost per m2.

![Figure 39 Middle-income affordable house layout for case study II](image-url)
2. **Evolver watcher**

Visualizing the convergence of the solution with respect to the number of trials and time is represented through Evolver watcher. Figure 40 gives an indication of the progression of the model in attempt to reach a near optimum solution. It further shows the convergence process and progress steps. The Evolver TM 5.5 optimization watcher shows the convergence of the solution along the iterations with a close-up graph focusing on the last 500 trials and another presenting all trials.

![Evolver TM 5.5 optimization screenshot](image)

Figure 40 Evolver TM 5.5 optimization screenshot of case study II

It gives an indication of the progression of the model in attempt to reach a near optimum solution. It further shows the convergence process and progress steps. As the iterative process continues and trials are made, the solution converges in an effort to reach a lower cost per m2.

3. **Optimization results**

Similar to Case I, initial constraints, code limitations, user architectural parametric ranges and specified limits are placed for Case II for the model to optimize and reach a nearer to optimum solution for the layout. Likewise, in this model the user further specified that beams should have no more than 6 steel bars for external beams and 4 steel bars for internal beams. The initial dimensions of the layout are input for the model to present the initial design before optimization. Figure 41 shows the initial layout for Case II before optimization. The model designed the structural elements based on this
layout, which are illustrated in Figure 42 and Table 20. Figure 42 shows the structural system configuration, reinforced concrete slab thickness, steel reinforcement for slabs, and reinforced concrete beam dimensions. Table 20 presents the steel reinforcement details for beams comprising of top, bottom and stirrups reinforcement. The sample design drawing before and after optimization is under Appendix III – Case II sample design drawing.

![Medium-income affordable house layout](image)

*Figure 41 Initial layout for Case II before optimization*
Figure 42 Initial design for Case II initial layout before optimization
The model is run where the optimization engine starts optimizing the initial layout presented in Figure 41 to achieve a layout with a lower cost per m2. The final layout for Case II after optimization is illustrated in Figure 43. Based on this layout, the model designed the final structural elements which are illustrated in Figure 44 and Table 21. Figure 44 shows the structural system configuration, reinforced concrete slab thickness, steel reinforcement for slabs, and reinforced concrete beam dimensions. Table 22 presents the steel reinforcement details for beams comprising of top, bottom and stirrups reinforcement.

### Table 20 Beam reinforcement details for Case II initial layout before optimization

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<thead>
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<td>2φ10</td>
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<tr>
<td></td>
<td>Bottom</td>
<td>5φ12</td>
<td></td>
<td>5φ10</td>
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Figure 43 Final layout for Case II after optimization

Figure 44 Final design for Case II final layout after optimization
Table 21 Beam reinforcement details for Case II final layout after optimization

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<td>9φ6/m</td>
<td>5φ6/m</td>
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</tr>
</tbody>
</table>

Table 22 presents the quantities of steel reinforcement, concrete, shuttering, as well as the GIUA, RC cost, RC cost per m2 to compare between the two layouts based on the constraints set and the initial layout of Case II. For example, a youth development project made up of 100 buildings each composed of 5 floors where each floor consists of 4 flats resulting in a total of 2000 flats. Comparing the final layout to initial layout, one would find that a decrease in cost of 14.22% equivalent to 14,229,220 LE with a decrease in area of 4.54% if the 2000 flats project is considered. The massive decrease in cost
coupled with the decrease in area achieved signifies the advantage of implementing optimization in the design of reinforced concrete floors.

Table 22 Comparison of initial layout and final layout for Case II

<table>
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<tr>
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<th>Initial</th>
<th>Final</th>
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<tbody>
<tr>
<td>Steel (kg)</td>
<td>2,107.60</td>
<td>1869.70</td>
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<tr>
<td>Concrete (m3)</td>
<td>21.58</td>
<td>17.91</td>
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<tr>
<td>Shuttering (m2)</td>
<td>223.16</td>
<td>190.74</td>
</tr>
<tr>
<td>GIUA (m2)</td>
<td>111.14</td>
<td>106.09</td>
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<tr>
<td>RC cost (LE)</td>
<td>50,019.30</td>
<td>42,904.69</td>
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<tr>
<td>RC cost per m2 (LE/m2)</td>
<td>450.05</td>
<td>404.43</td>
</tr>
<tr>
<td>RC cost of 2000 units (LE)</td>
<td>100,038,600</td>
<td>85,809,308</td>
</tr>
<tr>
<td>Cost savings (LE)</td>
<td>---</td>
<td>14,229,220</td>
</tr>
<tr>
<td>% Decrease in Cost</td>
<td>---</td>
<td>14.22</td>
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<tr>
<td>% Decrease in Area</td>
<td>---</td>
<td>4.54</td>
</tr>
</tbody>
</table>

D. Sensitivity analysis on Case II

1. Sensitivity analysis of concrete strength on optimization

Concrete strength is varied with all other variables the same to properly investigate its effect. It is varied with values 25, 30, 35 and 40 MPa. The sensitivity of the concrete strength is investigated on the optimization model. The overall and individual effect of the sensitivity of the concrete strength is examined on the reinforced concrete cost per m2, gross internal unit area and reinforced concrete cost. The data presented is the limits of each parameter and is plotted on the sensitivity charts for comparison.

Sensitivity of concrete strength on cost per m2

The lowest cost per m2 and highest cost per m2 are presented to indicate the range that may be achieved. The limits of the cost per m2 are useful in presenting the limitations of optimizing at this specific strength with the specified constraints. Table 23 presents the sensitivity of varying the concrete strength on the cost per m2. The lowest cost per m2 achieved for Case II: Middle-income affordable house is 386.89 LE/m2 at a concrete strength of 30MPa. This is dependent on the layout configuration.
One may notice on Figure 45 that there is a trend in the lower end of the range of the cost per m² where cost per m² decreases as the strength increases from 25MPa to 30MPa. Beyond 30MPa, the cost per m² starts to increase slightly as the concrete strength is increased due to the effect of concrete strength on the moment of resistance of the section. Despite the trend in the lower end, the higher end of the cost per m² shows that at 35MPa, the range is smaller. This is an advantage given that it has the low values of cost per m². Furthermore, increasing the strength to 40MPa would yield a larger range between the lowest and the highest cost per m².

![Sensitivity chart of concrete strength on concrete cost per m²](image)

**Table 23 Sensitivity of concrete strength on cost per m² of case study II**

<table>
<thead>
<tr>
<th>Concrete strength (MPa)</th>
<th>Lowest Cost/area (LE/m²)</th>
<th>Highest Cost/area (LE/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25MPa Fy360</td>
<td>404.43</td>
<td>487.01</td>
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<tr>
<td>30MPa Fy360</td>
<td>386.89</td>
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<td>389.77</td>
<td>451.18</td>
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<tr>
<td>40MPa Fy360</td>
<td>399.88</td>
<td>552.77</td>
</tr>
</tbody>
</table>

**Figure 45 Sensitivity of concrete strength on cost per m² of case study II**
Sensitivity of concrete strength on reinforced concrete cost

The lowest reinforced concrete cost and highest reinforced concrete cost are presented in Table 24 to indicate the range that may be achieved and present the sensitivity of varying the concrete strength on the reinforced concrete cost. The limits of the reinforced concrete cost are useful in presenting the limitations of optimizing at this specific strength with the specified constraints.

Table 24 Sensitivity of concrete strength on reinforced concrete cost of case study II

<table>
<thead>
<tr>
<th>Concrete strength (MPa)</th>
<th>Lowest Cost (LE)</th>
<th>Highest Cost (LE)</th>
</tr>
</thead>
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<tr>
<td>1 25MPa Fy360</td>
<td>34718.18</td>
<td>70508.73</td>
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<tr>
<td>2 30MPa Fy360</td>
<td>29564.18</td>
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</tr>
<tr>
<td>3 35MPa Fy360</td>
<td>29595.38</td>
<td>80062.97</td>
</tr>
<tr>
<td>4 40MPa Fy360</td>
<td>38298.63</td>
<td>85102.48</td>
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</table>

One may notice in Figure 46 that there is an apparent trend in the data. It is visible that increasing the strength from 25MPa to 30MPa would yield lower attainable reinforced concrete cost. Whereas increasing it beyond 35MPa to reach 40MPa would increase the reinforced concrete cost. The higher end of the reinforced concrete cost shows that at 25MPa, the range is relatively small. This is an advantage given that it has the lowest values of the reinforced concrete cost. Furthermore, increasing the strength to 30MPa would yield a larger range between the lowest and the highest cost per m2.
The lowest GIUA and highest GIUA are presented in Table 25 to indicate the range that may be achieved and show the sensitivity of varying the concrete strength on the Gross Internal Unit Area GIUA. The limits of the GIUA are useful in presenting the limitations of optimizing at this specific strength with the specified constraints.

### Table 25 Sensitivity of concrete strength on gross internal unit area of case study II

<table>
<thead>
<tr>
<th>Concrete strength (MPa)</th>
<th>Lowest GIUA (m²)</th>
<th>Highest GIUA (m²)</th>
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<tbody>
<tr>
<td>1 25MPa Fy360</td>
<td>82.56</td>
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<td>2 30MPa Fy360</td>
<td>74.65</td>
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<td>3 35MPa Fy360</td>
<td>73.96</td>
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</tr>
<tr>
<td>4 40MPa Fy360</td>
<td>91.33</td>
<td>183.47</td>
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</table>

One may notice on Figure 47 that there is a trend in the lower end of the range of the GIUA. It is visible that increasing the strength from 25MPa to 30MPa would yield lower attainable GIUA. Whereas increasing it beyond 35MPa to reach 40MPa would increase the GIUA. It is visible that the higher end of the GIUA shows that at 30MPa and
35MPa, the range is relatively high. Furthermore, increasing the strength to 40MPa or decreasing it to 25MPa would yield a smaller range between the lowest and the highest GIUA.

![Sensitivity chart of concrete strength on gross internal unit area](image)

**Figure 47 Sensitivity of concrete strength on gross internal unit area of case study II**

2. **Optimization output for sensitivity analysis of concrete strength**

   The relationship between the gross internal unit area and the reinforced concrete cost per m² is illustrated in Figure 48, Figure 50, Figure 52 and Figure 54. Graphs presented in the figures are based on the layout of Figure 39 run for 5,000 trials. It signifies the multiple values of reinforced concrete cost per m² for the same area with a variation in the layout. Likewise, the graphs presented indicate multiple areas for the same reinforced concrete cost per m² for different layouts. As the area of the floor increases, a decrease in the cost per m² of the floor is witnessed up until the lowest point on the graph where the cost per m² increases with an increase in the area. The correlation in the figure presented indicates the same trend as the one for Case I. One may notice that the near optimum solution that the model would give is the point with the lowest cost per
m2 is. Varying the concrete strength as presented in the graphs would alter the lowest point, the correlation of the graph, intensity of points and their distribution. Similar to Case I, results are clustered into groups to illustrate the relationship between the reinforced concrete cost per m2 and the GIUA. A non-linear relationship is noticed on the regression curves.

Figure 49, Figure 51, Figure 53 and Figure 55 present graphs of the GIUA vs. reinforced concrete cost to illustrate the relationship between the gross internal unit area and the reinforced concrete cost. 5,000 trials are run on the layout of Figure 39 to output the various layouts presented on the graphs. The correlation and multiple values of concrete unit cost for the same unit area are signified through the graphs. Likewise, multiple areas for the same concrete cost are indicated. The relationship between the reinforced concrete cost per m2 and the GIUA is illustrated through the regression lines of the clustered results. Linear relationship is presented through the correlation present and plotted regression lines.

Outliers that are not consistent with the regression or the trend of the graph are clustered in a couple of small groups. An inefficient design that significantly increases the reinforced concrete cost per m2 may be the result of the outliers. Jumps between various layouts are illustrated on the graph in the clusters where they signify the a shift in the design due to maximum and minimum steel reinforcement specified for slabs and beams, specific commercially available steel bar diameters, minimum number of steel reinforcement bars and minimum spacing between steel reinforcement bars. The model is driven to optimize and achieve a larger area for a lower cost per m2 due to variations between the required area of steel and the selected one and minimum number of bars in beams and slabs. Concrete as well has an impact in the jumps witnessed on the graph where they may be due to minimum dimensions of elements, specific increments of dimensions and unified dimensions for specific elements.
**Optimization output for $F_{cu} = 25 \text{ MPa}$**

**Figure 48** Gross internal unit area vs. reinforced concrete cost per m² for $F_{cu} = 25 \text{ MPa}$ for case study II

**Figure 49** Gross internal unit area vs. reinforced concrete cost for $F_{cu} = 25 \text{ MPa}$ for case study II
**Optimization output for Fcu = 30 MPa**

**Figure 50** Gross internal unit area vs. reinforced concrete cost per m² for Fcu = 30 MPa for case study II

**Figure 51** Gross internal unit area vs. reinforced concrete cost for Fcu = 30 MPa for case study II
Optimization output for $F_{cu} = 35$ MPa

Figure 52 Gross internal unit area vs. reinforced concrete cost per m$^2$ for $F_{cu} = 35$ MPa for case study II

Figure 53 Gross internal unit area vs. reinforced concrete cost for $F_{cu} = 35$ MPa for case study II
Optimization output for $F_{cu} = 40$ MPa

Figure 54 Gross internal unit area vs. reinforced concrete cost per m$^2$ for $F_{cu} = 40$ MPa for case study II

Figure 55 Gross internal unit area vs. reinforced concrete cost for $F_{cu} = 40$ MPa for case study II
V. CONCLUSION

A. Conclusion

The model presented exploits the variations in the cost versus area graph through optimizing the cost of houses that have the same cost with different areas, same areas with different costs and optimized areas within a specified budget or budget range. Available options are tailored to optimize the reinforced concrete floor cost of housing units through varying the dimensions of the rooms. The model is able to optimize housing units within a specified budget to result in layouts with different areas where the model would elect the layout with the least cost per m². In addition, it is able to optimize housing units within a specified area range to result in layouts with varying cost where the model would prefer the layout with least cost per m². Costs incorporated are based on the Egyptian construction market cost data of January 2015 and the design is based on the Egyptian Code of Practice 2007 for design of reinforced concrete structures. The optimization of the architectural parametric variables, defined limits, parameters and constraints is based on optimizing the architectural restrictions per room and unifying the area to achieve the lowest cost. Furthermore, the model is customizable in a sense that it gives the user the ability to adjust all the structural design parameters, architectural dimensional parameters with ranges for the model to optimize and select the most suitable and efficient design for the housing unit as per the defined constraints. The model further generates the proposed layouts along with their Bill of Quantities.

B. Research findings

The proposed model presents a gap in the research of affordable housing that aims to mutually benefit developers and housing residents. It is evident that affordable housing is a necessity for our society. Reviewing previous literature and further developing on it is an attempt to fill the gap in research. The major finding in this research is:

- Optimizing the initial design such that it results in a final design that exhibits a larger gross internal unit area with a lower reinforced concrete cost.

Other significant findings complement the major finding as follows:
The proposed model would further enhance the link between architectural parametric designs and structural design through the utilization of a range for each dimension. The range for each parametric dimension allows the optimization processor to better optimize results in an effort to reach near optimum solutions.

Through exploiting the variations in the reinforced concrete cost versus gross internal unit area, one would have layouts having the same area but at different costs. Likewise, there are layouts having the same cost but with different areas. Therefore, this offers decision makers, developers, investors and project stakeholders the ability to optimize based on several approaches.

The optimization offers users the ability to optimize their design based on architectural restrictions per room and result in a number of optimized layouts along with the near optimum layout. In addition, the user is able to unify the area and optimize based on a preferred area resulting in a layout with the same area at a lower cost.

It should be noted that through the variation in layout, one may notice that for larger rooms, the model favors the room to be a square rather than rectangle such that the load from slabs be equally distributed on all sides. However, if the aspect ratio increases, the majority of the load will be transferred in the short direction that will increase the concrete dimensions and reinforcement of the supporting beams thus leading to an increased cost. Large rooms will have the highest impact on the overall cost. It is recommended that the largest rooms be taken as a square as square elements are more efficient. The degree of rectangularity has an effect on the degree of reinforcement and thus has an effect on the cost.

The model has been applied on 2 case studies for validation and it showed promising results. In Case I, the model showed more promising results with higher variation between the plotted points which gives more room for optimization to save costs. In Case II, significant savings were made as well. The varying layouts affected the output of the case studies.

The points selected showed that one would be able to decrease the cost by 15.04% with an increase in area by 0.22%. Further, one would be able to decrease the cost by
14.97% with an increase in area by 1.88%. These percentages are dependent on the selected examples. More saving may be achieved. However, this is dependent largely on the initial design of the model.

Further to this, the sensitivity analysis performed gave some insight about trends:

- For Case I: Low-income affordable house, one may notice the trend in the lower end of the range of the cost per m². One may notice the trend in the lower end of the range of the cost per m². It is visible that increasing the concrete strength would yield a nearer to optimum solution as compared to lower concrete strength. However, the decrease between 30MPa and 35MPa and increase between 35MPa and 40MPa are not significant. The lowest cost per m² achieved for Case I: Low-income affordable house is 471.32 LE/m² at a concrete strength of 35MPa.

- For Case II: Middle-income affordable house, there is a trend in the lower end of the range of the cost per m². It is evident that the cost per m² decreases as the strength increases from 25MPa to 30MPa. Beyond 30MPa, the cost per m² starts to increase slightly as the concrete strength is increased. The lowest cost per m² achieved for Case II: Middle-income affordable house is 386.89LE/m² at a concrete strength of 30MPa.

- The effect of the concrete strength on the cost per m² typically decreases as you increase the concrete strength. However, beyond a certain point, the cost per m² increases with an increase in concrete strength due to the effect of concrete strength on the moment of resistance of the section.

Since Case II achieved a lower cost per m² compared to Case I, the layout highly impacts the sensitivity of reinforced concrete strength and the lowest cost per m².

- This may be attributed to the fact that Case I structural configuration had beams carrying other beams and not all supported on columns.

- In addition, the relative room sizes and parametric ranges of Case II are higher than in Case I which may have had an impact on the solution. Since the cost of beams is proportional to their length, dividing the cost of beams by a smaller area in low income houses leads to a higher cost per m². Whereas, dividing it by a bigger area in middle income houses leads to a lower cost per m².
C. Recommendations

Despite the ability of the proposed model to fill the gap in the literature, there is still room for enhancement and improvement for more efficient and accurate results. Below is a list of recommendations for future researchers and applicators:

- Establish an efficiency index that calibrates the efficiency through the sum product of the area by the degree of rectangularity or aspect ratio of each room
- Life cycle optimization of reinforced concrete structural elements should be considered taking into account the maintenance costs and service life of the various elements and materials used
- Integrating a more accurate analysis software that would automatically analyze and report the moment and shear values to the model rather than relying on approximate methods such as the three moment equation
- Apply the model on multi-story buildings and comparing the multi-story results with results from a single floor
- Incorporating the design of the foundations and columns in the model considering the effect of the additional weight and configuration on foundation design and costs
- Incorporating Building Information Modeling BIM parametric ranges with the structural design module to have a complete design process
- Integrating the time dimension in the reinforced concrete design optimization to simulate and optimize the construction process
- Investigate various optimization techniques apart from genetic algorithms on several layouts: memetic algorithms, ant colony, shuffled frog leaping, particle swarm and others, and comparing their results to examine their efficiencies and sensitivity
REFERENCES


APPENDIX I – DESIGN MODULE

A. Design of slabs

1. Concrete dimensions

Slab thickness cannot be less than 8cm as per the Egyptian Code limitation.

1. Check two-way or one-way slab using the aspect ratio:

\[ r = \frac{b}{a} < 2 \iff \text{two-way slab} \]
\[ r = \frac{b}{a} \geq 2 \iff \text{one-way slab} \]

![Diagram](image)

Figure 56 Load distributions on one-way and two-slabs

2. Get Slab thickness

<table>
<thead>
<tr>
<th>Table 26 Slab thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-way slab thickness (m)</td>
</tr>
<tr>
<td>--------------------------</td>
</tr>
<tr>
<td>Simply supported</td>
</tr>
<tr>
<td>Continuous from one side</td>
</tr>
<tr>
<td>Continuous from both sides</td>
</tr>
<tr>
<td>Cantilever</td>
</tr>
</tbody>
</table>

Note: Slab thickness is calculated using the shorter slab dimension as it is governed by the short span. \( \beta_p \) represents the ratio of continuous perimeter to total perimeter for each
slab. It is taken as 1 for slabs continuous from sides, 0.75 for slabs continuous from one side and 0.5 for simply supported slabs.

2. **Loads calculation**

**Dead load**

Own weight

\[ \text{ow} = \gamma_c t_s \]

Weight of slab dead load

\[ w_{sDL} = \gamma_c t_s + \text{flooring} \ [\text{selected}] \]

Note: The flooring load is determined by the flooring finish cover, plastering, isolation and insulation materials, false ceiling and lights, decorative materials and MEP fixtures.

**Live load**

Weight of slab live load

\[ w_{sLL} = [\text{selected}] \]

Note: The live load is selected according to the purpose of the building as per the Egyptian Code.

**Load distribution**

Load is distributed as per the load distribution layout in a trapezoidal and triangular distribution with coefficients \( \beta \) and \( \alpha \).

<table>
<thead>
<tr>
<th>Table 27 Factor of two-way slab load distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_1 )</td>
</tr>
<tr>
<td>-------------</td>
</tr>
<tr>
<td>Simply supported</td>
</tr>
<tr>
<td>Continuous from one side</td>
</tr>
<tr>
<td>Continuous from both sides</td>
</tr>
</tbody>
</table>
Table 28 Load distribution for two-way solid slabs

<table>
<thead>
<tr>
<th>$r = \frac{bm_1}{am_2}$</th>
<th>1</th>
<th>1.1</th>
<th>1.2</th>
<th>1.3</th>
<th>1.4</th>
<th>1.5</th>
<th>1.6</th>
<th>1.7</th>
<th>1.8</th>
<th>1.9</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>0.35</td>
<td>0.4</td>
<td>0.45</td>
<td>0.5</td>
<td>0.55</td>
<td>0.6</td>
<td>0.65</td>
<td>0.7</td>
<td>0.75</td>
<td>0.8</td>
<td>0.85</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.35</td>
<td>0.29</td>
<td>0.25</td>
<td>0.21</td>
<td>0.18</td>
<td>0.16</td>
<td>0.14</td>
<td>0.12</td>
<td>0.11</td>
<td>0.09</td>
<td>0.08</td>
</tr>
</tbody>
</table>

**Slab ultimate loads**

The ratio of the weight of the live load moment to the weight of the dead load moment determines the ultimate load factors for the calculation of the weight of the ultimate moments.

$$\frac{w_{sLL}}{w_{SDL}} \leq 0.75 \therefore w_{UL} = 1.5(w_{SDL} + w_{sLL})$$

$$\frac{w_{sLL}}{w_{SDL}} > 0.75 \therefore w_{UL} = 1.4(w_{SDL}) + 1.6(w_{sLL})$$

**Slab equivalent loads**

Equivalent loads are developed for ease of calculation as per the below equations for the weight of the slab dead load and live load for moment. This is only for the two-way slab. For the one-way slab, the ultimate weight of slab is directly used with no factoring.

Weight of slab ultimate load in short direction

$$w_{s\alpha} = w_{SU} x \alpha$$

Weight of slab ultimate load in long direction

$$w_{s\beta} = w_{SU} x \beta$$
3. Analysis

**Moment calculation using code coefficient**

This is valid for 2 spans and more than 2 spans as per the below diagrams

![Figure 57 Code coefficient ultimate moment calculations for 2 spans of slabs](image)

![Figure 58 Code coefficient ultimate moment calculations for more than 2 spans of slabs](image)

Despite the ease of application of the code coefficient, it has a number of limitations as below:

- No variation in neighboring spans greater than 20%
- No variation in neighboring loads greater than 20%
- No concentrated loads
- No cantilevers

Such limitations tend to elect the French equation.
Moment calculation using French equation

With these limitations in the code coefficient method, the French equation would be a better option for a more universal calculation where these limitations are no longer an obstacle for the ultimate moment and shear calculations.

The ultimate moment from uniform load is calculated as follows:

\[
M = \frac{w_L L_L^3 + w_R L_R^3}{8.5(L_L + L_R)}
\]

Figure 59 French equation ultimate moment calculations for uniform loads

In addition to the mid span and mid support moment calculations, the Egyptian Code assumes there is a moment at the end supports equivalent to \( \frac{w l^2}{24} \) for fixation provisions.

In slab design, the shear force has to be resisted by the concrete as there is no shear reinforcement for slabs.

At end supports

\[
V_{end \ support} = \frac{w l^2}{2} - \frac{M_{middle \ support \ moment}}{L}
\]

At middle support

\[
V_{middle \ support} = (w_1 L_1 + w_2 L_2) - V_{end \ support \ 1} - V_{end \ support \ 2}
\]
Since the live load constitutes approximately 40% of the weight of the structure and will not have a significant impact, no cases of loading were considered and it is assumed that the live load is distributed everywhere all the time.

4. Design

One way slabs

The design of the one way slab follows the below set of steps:

1. Effective length $L$ is the smaller of:
   a. $L = C_L \cdot t$ or $C_L$
   b. The larger of:
      i. $L = L_{clear \ span} + t_s$
      ii. $L = 1.05 \cdot L_{clear \ span}$

Note: $L$ is considered to be the effective length of the design.

2. Determine $M_U$ at each critical section using the French Equation

3. Select clear cover $cc$

<table>
<thead>
<tr>
<th>Category</th>
<th>All elements except solid slabs &amp; walls</th>
<th>Walls &amp; solid slabs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$F_{cu} \leq 25$</td>
<td>$F_{cu} &gt; 25$</td>
</tr>
<tr>
<td>One</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>Two</td>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td>Three</td>
<td>35</td>
<td>30</td>
</tr>
<tr>
<td>Four</td>
<td>45</td>
<td>40</td>
</tr>
</tbody>
</table>

Note: Each category represents a degree of exposure to environmental conditions.

Category One: Structure with protected tension sides
Category Two: Structure with unprotected tension sides
Category Three: Structure with severely exposed tension sides
Category Four: Structures with tension sides very severely exposed to corrosive chemical attacks.

4. Cover $c = cc + \frac{\theta_{bar}}{2}$

5. Effective depth $d$

$$d = t_s - c$$

In slab design, the shear force has to be resisted by the concrete as there is no shear reinforcement for slabs.

6. Shear force
   a. At end supports

$$V_{end\ support} = \frac{wt^2}{2} - M_{middle\ support\ moment}$$

   b. At middle support

$$V_{middle\ support} = (w_1L_1 + w_2L_2) - V_{end\ support\ 1} - V_{end\ support\ 2}$$

7. Ultimate shear

$$Q_U = V - \left(\frac{c}{2} + \frac{d}{2}\right)xw_U$$

8. Ultimate shear stress

$$q_U = \frac{Q_U}{1000xd} \leq 0.16 \sqrt{\frac{F_{cu}}{\gamma_c}}$$

   a. If $q_U$ is less than or equal, then continue.

   b. If $q_U$ is more than, then increase $t_s$.

9. $R_u = \frac{M_{u}x10^6}{1000xd^2}$

10. $\mu_{computed}$ is obtained from the $R_u$ tables using

   a. $F_{cu}$: 25, 30, 35, 40

   b. $F_y$: 240, 280, 360, 400, 450

   c. $R_u$: Varies based on $\mu$
11. $\mu_{\text{min}}$
   a. For high tensile steel, $\mu_{\text{min}} = 0.0015$
   b. For mild steel, $\mu_{\text{min}} = 0.0025$

12. $\mu_{\text{slab}}$ is the larger of:
   a. $\mu_{\text{computed}}$
   b. $\mu_{\text{min}}$

13. $A_{s_{\text{slab}}} = \mu_{\text{slab}} \times 1000xd$

14. Using $A_{s_{\text{slab}}}$, select the nearest $A_s$ to be $A_{s_{\text{actual}}}$

Table 30: Steel bars commercially used in Egypt for slabs

<table>
<thead>
<tr>
<th>Ø (mm)</th>
<th>Weight (Kg/m)</th>
<th>Circum (cm)</th>
<th>Area of Cross-Section (cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>1.58</td>
<td>5.03</td>
<td>8.04 10.1 12.1 14.1 16.1 18.1 20.1</td>
</tr>
<tr>
<td>12</td>
<td>0.888</td>
<td>3.77</td>
<td>4.52 5.65 6.79 7.92 9.05 10.2 11.3</td>
</tr>
<tr>
<td>10</td>
<td>0.617</td>
<td>3.14</td>
<td>3.14 3.93 4.71 5.5 6.28 7.07 7.85</td>
</tr>
</tbody>
</table>

15. Extract $A_{s_{\text{actual}}}$ properties
   a. Diameter of main steel rebar $\varnothing_{\text{bars}}$
   b. Number of steel bars $n$
   c. Weight of steel bars $w_{\text{bars}}/m$
   d. Circumference of steel bars $\text{Circum}$

16. $S_{\text{min}} = 100mm$

17. $S_{\text{max}}$ is smaller of:
   a. $2t_s$
   b. 200mm

18. Minimum number of bars/m = \frac{1000}{S}$

19. Length of steel bars
   a. At support $L_{\text{bars}} = \frac{L}{4}$
   b. At span $L_{\text{bars}} = L$
Weight of steel bars

\[ w_{\text{bars}} = \frac{w_{\text{bars}}}{m \times L_{\text{bars}}} \]

Number of steel bars

\[ n_{\text{bars}} = \text{Minimum number of bars} / m \times W \]

Weight of steel bars total

\[ w_{\text{bars total}} = w_{\text{bars}} \times W \]

Secondary steel area

\[ A_{\text{secondary}} = 20\% \text{ of } A_{\text{slab}} \]

Two way slabs

The design of the two way slab follows the below set of steps:

1. Effective length \( L \) is the smaller of:
   a. \( L = C_L \times t \times C_L \)
   b. The larger of:
      i. \( L = L_{\text{clear span}} + t_s \)
      ii. \( L = 1.05 \times L_{\text{clear span}} \)

   Note: \( L \) is considered to be the effective length of the design.

2. Determine \( M_U \) at each critical section using the French Equation

3. Select clear cover \( cc \)

4. Cover \( c = cc + \frac{\varphi_{\text{bar}}}{2} \)

5. Effective depth \( d \)

\[ d = t_s - c \]

6. Ultimate shear

\[ Q_U = V - \left( \frac{c}{2} + \frac{d}{2} \right) x w_U \]

7. Ultimate shear stress

\[ q_U = \frac{Q_U}{1000 x d} \leq 0.16 \sqrt[2]{\frac{F_{cu}}{Y_c}} \]
a. If $q_U$ is less than or equal, then continue.
b. If $q_U$ is more than, then increase $t_s$.

8. $$R_u = \frac{M_u \times 10^6}{1000 \times d^2}$$

9. $\mu_{\text{computed}}$ is obtained from the $R_u$ tables using
   a. $F_{cu}$: 25, 30, 35, 40
   b. $F_y$: 240, 280, 360, 400, 450
   c. $R_u$: Varies based on $u$

10. $\mu_{\text{min}}$
   a. For high tensile steel, $\mu_{\text{min}} = 0.0015$
   b. For mild steel, $\mu_{\text{min}} = 0.0025$

11. $\mu_{\text{slab}}$ is the larger of:
   a. $\mu_{\text{computed}}$
   b. $\mu_{\text{min}}$

12. $$A_{s_{\text{slab}}} = \mu_{s_{\text{lab}}} \times 1000xd$$

13. Using $A_{s_{\text{slab}}}$, select the nearest $A_s$ to be $A_{s_{\text{actual}}}$

14. Extract $A_{s_{\text{actual}}}$ properties
   a. Diameter of main steel rebar $\varnothing_{bars}$
   b. Number of steel bars $n$
   c. Weight of steel bars $w_{bars}/m$
   d. Circumference of steel bars $Circum$

15. $S_{\text{min}} = 100mm$

16. $S_{\text{max}}$ is smaller of:
   a. $2t_s$
   b. 200mm

17. Minimum number of bars/m = $\frac{1000}{S}$

18. Length of steel bars
   a. At support $L_{bars} = \frac{L}{4}$
   b. At span $L_{bars} = L$
19. Weight of steel bars

\[ w_{bars} = w_{bars} / m \times L_{bars} \]

20. Number of steel bars

\[ n_{bars} = \text{Minimum number of bars} / m \times W \]

21. Weight of steel bars total

\[ w_{bars\ total} = w_{bars} \times W \]

B. Design of beams

1. Concrete dimensions

Beam depth cannot be:

- Less than 3 times the slab thickness \( t_s \)
- Greater than the difference between the floor height \( H \) and the recommended door height including floor finish (typically 2.3m). Assuming \( H \) as 3m, then the beam depth cannot exceed 0.7m.

Get beam depth:

<table>
<thead>
<tr>
<th>Table 31 Beam depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam depth (m)</td>
</tr>
<tr>
<td>Simply supported</td>
</tr>
<tr>
<td>Continuous from one side</td>
</tr>
<tr>
<td>Continuous from both sides</td>
</tr>
<tr>
<td>Cantilever</td>
</tr>
</tbody>
</table>

2. Loads calculation

**Dead load**

Own weight

\[ ow = \gamma_c(h - t_s)b \]
Weight of plaster

\[ w_{plaster} = \gamma_p (H - h) t_p \]

Weight of wall

\[ w_{wall} = \gamma_w (H - h) b = w(H - h) \]

Weight of slab dead load

\[ w_{s_{DL}} = \gamma_c t_s + flooring \ [selected] \]

Note: The flooring load is determined by the flooring finish cover, plastering, isolation and insulation materials, false ceiling and lights, decorative materials and MEP fixtures.

**Live load**

Weight of slab live load

\[ w_{s_{LL}} = [selected] \]

Note: The live load is selected according to the purpose of the building as per the Egyptian Code.

**Load distribution**

Load is distributed as per the load distribution layout where coefficients \( \beta \) and \( \alpha \) refer to load coefficients for calculating moments and shear.

<table>
<thead>
<tr>
<th>( r ) = ( \frac{b}{a} )</th>
<th>1</th>
<th>1.1</th>
<th>1.2</th>
<th>1.3</th>
<th>1.4</th>
<th>1.5</th>
<th>1.6</th>
<th>1.7</th>
<th>1.8</th>
<th>1.9</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha )</td>
<td>0.667</td>
<td>0.725</td>
<td>0.769</td>
<td>0.803</td>
<td>0.829</td>
<td>0.852</td>
<td>0.87</td>
<td>0.885</td>
<td>0.897</td>
<td>0.908</td>
<td>0.917</td>
</tr>
<tr>
<td>( \beta )</td>
<td>0.5</td>
<td>0.545</td>
<td>0.583</td>
<td>0.615</td>
<td>0.643</td>
<td>0.667</td>
<td>0.688</td>
<td>0.706</td>
<td>0.722</td>
<td>0.737</td>
<td>0.75</td>
</tr>
</tbody>
</table>

**Beam equivalent loads**

Equivalent loads are developed for ease of calculation as per the below equations for the weight of the dead load and live load for moment and shear.
Weight of live load moment

\[ w_{LL_{moment}} = w_{SLL} \times \frac{a}{2} x \alpha \]

Weight of dead load moment

\[ w_{DL_{moment}} = ow + w_{wall} + (w_{SDL} \times \frac{a}{2} x \alpha) \]

Weight of live load shear

\[ w_{LL_{shear}} = w_{SLL} \times \frac{a}{2} x \beta \]

Weight of dead load shear

\[ w_{DL_{shear}} = ow + w_{wall} + (w_{SDL} \times \frac{a}{2} x \beta) \]

**Beam ultimate loads**

The ratio of the weight of the live load moment to the weight of the dead load moment determines the ultimate load factors for the calculation of the weight of the ultimate moments.

\[ \frac{w_{LL_{moment}}}{w_{DL_{moment}}} \leq 0.75 \therefore w_{U_{moment}} = 1.5(w_{DL_{moment}} + w_{LL_{moment}}) \]

\[ \frac{w_{LL_{moment}}}{w_{DL_{moment}}} > 0.75 \therefore w_{U_{moment}} = 1.4(w_{DL_{moment}}) + 1.6(w_{LL_{moment}}) \]

The ratio of the weight of the live load shear to the weight of the dead load shear determines the ultimate load factors for the calculation of the weight of the ultimate shear.

\[ \frac{w_{LL_{shear}}}{w_{DL_{shear}}} \leq 0.75 \therefore w_{U_{shear}} = 1.5(w_{DL_{shear}} + w_{LL_{shear}}) \]

\[ \frac{w_{LL_{shear}}}{w_{DL_{shear}}} > 0.75 \therefore w_{U_{shear}} = 1.4(w_{DL_{shear}}) + 1.6(w_{LL_{shear}}) \]
3. Analysis

*Moment and shear calculation using code coefficient*

This is valid for 2 spans and more than 2 spans as per the below diagrams

---

**Figure 60** Code coefficient ultimate moment calculations for 2 spans of beams

**Figure 61** Code coefficient ultimate shear calculations for 2 spans of beams

**Figure 62** Code coefficient ultimate moment calculations for more than 2 spans of beams
Despite the ease of application of the code coefficient, it has a number of limitations as below:

- No variation in neighboring spans greater than 20%
- No variation in neighboring loads greater than 20%
- No concentrated loads
- No cantilevers

Such limitations tend to elect the French equation.

**Moment and shear calculation using French equation**

With these limitations in the code coefficient method, the French equation would be a better option for a more universal calculation where these limitations are no longer an obstacle for the ultimate moment and shear calculations.

The ultimate moment from uniform load is calculated as follows:

$$M = \frac{w_L L_L^3 + w_R L_R^3}{8.5(L_L + L_R)}$$
The ultimate moment from concentrated forces is calculated as follows:

\[ M = \frac{K_L P_L L_L^2 + K_R P_R L_R^2}{L_L + L_R} \]

In the case where there is both a uniform load along with a concentrated force, the moments resulting from both equations are added to result in the ultimate moment at this section denoted by \( M_U \).
\[ M_U = \frac{w_L L_L^3}{8.5(L_L + L_R)} + \frac{K_L P_L L_L^2}{L_L + L_R} + \frac{K_R P_R L_R^2}{L_L + L_R} \]

Note: \( L = 0.8 \) L in the case where the span is continuous from both sides.

The K factor is obtained from the table below using the ratio \( a/L \).

<table>
<thead>
<tr>
<th>( a/L )</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
<th>0.9</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>0.08</td>
<td>0.136</td>
<td>0.168</td>
<td>0.182</td>
<td>0.176</td>
<td>0.158</td>
<td>0.128</td>
<td>0.09</td>
<td>0.05</td>
<td>0</td>
</tr>
</tbody>
</table>

In addition to the mid span and mid support moment calculations, the Egyptian Code assumes there is a moment at the end supports equivalent to \( \frac{w l^2}{24} \) for fixation provisions.

The ultimate shear is calculated using the moment of the middle support as follows:

At end supports

\[ V_{end\ support} = \frac{\frac{w l^2}{2} - M_{middle\ support\ moment}}{L} \]

At middle support

\[ V_{middle\ support} = (w_1 L_1 + w_2 L_2) - V_{end\ support\ 1} - V_{end\ support\ 2} \]

Since the live load constitutes no more than 30\% of the weight of the structure and will not have a significant impact, no cases of loading were considered and it is assumed that the live load is distributed everywhere all the time.
4. Design

Positive section moment

The design of the positive section follows the below set of steps:

1. Cover $c$.

<table>
<thead>
<tr>
<th>Moment $M_U$ (Nm)</th>
<th>Cover $c$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than $&lt;100$</td>
<td>50</td>
</tr>
<tr>
<td>Greater than $&gt;100$</td>
<td>60</td>
</tr>
<tr>
<td>Greater than $&gt;1000$</td>
<td>70</td>
</tr>
</tbody>
</table>

2. Effective depth $d$

$$d = h - \text{cover}$$

3. $n_w$ is obtained from the below table:

<table>
<thead>
<tr>
<th></th>
<th>T-section</th>
<th>L-section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simply supported</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Continuous from one side</td>
<td>0.85</td>
<td>0.85</td>
</tr>
<tr>
<td>Continuous from both sides</td>
<td>0.7</td>
<td>---</td>
</tr>
</tbody>
</table>

4. Effective width at compression side $B$

The width $B$ is dependent on the type of section through a set of equations. The types of sections are T-section where the beam is in between two spans and the other is the L-section in the case of an edge beam.
a. **T-section**

![Figure 66 T-section beam](image)

$B$ is the smallest of the (i), (ii) and (iii)

i. $B = C_L$ to $C_L = \frac{l_k}{2} + \frac{l_B}{2}$

ii. $B = 16t_s + b$

iii. $B = \frac{n_wL}{5} + b$

b. **L-section**

![Figure 67 L-section beam](image)

$B$ is the smallest of the (i), (ii) and (iii)

i. $B = C_L$ to edge $= \frac{L}{2} + \frac{b}{2}$

ii. $B = 6t_s + b$

iii. $B = \frac{n_wL}{10} + b$

Assume $a_{comp\; dept\; h} = t_s$

![Figure 68 Equivalent rectangular section with width B where a=ts](image)

5. $M_1 = 0.45F_{cu}Bt_s \left( d - \frac{t_s}{2} \right)$

If $M_{ul} < M_1 \therefore a_{comp\; dept\; h} < t_s$, therefore Case (I)
Figure 69 Equivalent rectangular section with width B where a<ts

6. \[ R_u = \frac{M_u \times 10^6}{Bd^2} \]

7. \( \mu_{maximum} \) is obtained from the \( R_u \) tables using
   a. \( F_{cu} : 25, 30, 35, 40 \)
   b. \( F_y : 240, 280, 360, 400, 450 \)

8. \( \mu_{computed} \) is obtained from the \( R_u \) tables using
   a. \( F_{cu} : 25, 30, 35, 40 \)
   b. \( F_y : 240, 280, 360, 400, 450 \)
   c. \( R_u : \text{Varies based on } u \)

If \( \mu_{computed} \gg \mu_{maximum} \), then either increase the depth of the section \( d \) or add compression steel.

9. \( A_{s computed} = \mu_{computed} Bd \)

10. \( \mu_{min} \)
    a. For high tensile steel, \( \mu_{min} \) should be the smallest of \( \frac{1.1}{F_y} \) and 0.0015
    b. For mild steel, \( \mu_{min} \) should be the smallest of \( 1.33 \mu_{comp} \) and 0.0025

This ensures that ductility and shrinkage do not result in a brittle failure, but in a ductile failure.

11. \( A_{s_{min \ (1)}} = \mu_{min} bd \)

12. \( A_{s_{min \ (2)}} = \frac{M_u \times 10^6}{0.87F_y 0.95d} \)

13. \( A_{s_{calculated}} \) is the largest of \( A_{s_{computed}}, A_{s_{min \ (1)}}, \) and \( A_{s_{min \ (2)}} \)
    a. \( A_{s_{computed}} \)
b. \( A_{s_{\text{min}}} \) (1)

c. \( A_{s_{\text{min}}} \) (2)

14. Using \( A_{s_{\text{calculated}}} \), select the nearest \( A_s \) to be \( A_{s_{\text{actual}}} \)

<table>
<thead>
<tr>
<th>Ø (mm)</th>
<th>Weight (Kg/m)</th>
<th>Circum (cm)</th>
<th>Area of cross section (cm(^2))</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>22</td>
<td>2.98</td>
<td>6.91</td>
<td>7.6</td>
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<tr>
<td>18</td>
<td>2</td>
<td>5.65</td>
<td>5.09</td>
</tr>
<tr>
<td>16</td>
<td>1.58</td>
<td>5.03</td>
<td>4.02</td>
</tr>
<tr>
<td>12</td>
<td>0.888</td>
<td>3.77</td>
<td>2.26</td>
</tr>
<tr>
<td>10</td>
<td>0.617</td>
<td>3.14</td>
<td>1.57</td>
</tr>
</tbody>
</table>

15. Check the maximum number of bars \( n_{1_{\text{row}}} \) that fit in one row

a. Select clear cover \( c \)

b. Calculate \( n \)

\[
b = 2c + 2\varnothing_{\text{stirrups}} + n_{1_{\text{row}}} \varnothing_{\text{bars}} \]

\[
+ (n_{1_{\text{row}}} - 1) \times \text{Least allowable spacing between bars}
\]

\[
\therefore \ n_{1_{\text{row}}}
\]

\[
b - 2xc - 2\varnothing_{\text{stirrups}} + \text{Least allowable spacing between bars} \]

\[
\varnothing_{\text{bars}} + \text{Least allowable spacing between bars}
\]

The least allowable spacing between bars is typically 25mm.

c. Round \( n_{1_{\text{row}}} \) down to the nearest integer

16. Calculate \( d_{\text{actual}} \)

a. Calculate \( c_{\text{actual}} \)

i. If 1 row: \( c_{\text{actual}} = c + \varnothing_{\text{stirrups}} + \frac{\varnothing_{\text{bars}}}{2} \)
ii. If 2 rows: 
\[ c_{actual} = cc + \emptyset_{stirrups} + \emptyset_{bars} + \] 
\[ \text{Least allowable spacing between bars} \] 
\[ \frac{2}{2} \]

b. \[ d_{actual} = h - c_{actual} \]

17. Calculate \( \mu_{actual} \)

\[ \mu_{actual} = \frac{A_{s_{actual}} (mm^2) \times 10^2}{bd_{actual}} \]

18. \( R_u \) is obtained from the \( R_u \) tables using

a. \( F_{cu} : 25, 30, 35, 40 \)

b. \( F_{y} : 240, 280, 360, 400, 450 \)

c. \( \mu_{actual} : \) Varies based on \( R_u \)

19. \( M_r = \frac{R_u b d_{actual}}{10^6} \)

20. Economy ratio

a. If \( \frac{M_u}{M_r} < 0.9 \) \( \therefore \) uneconomic

b. If \( 0.9 \leq \frac{M_u}{M_r} < 1 \) \( \therefore \) economic

c. If \( \frac{M_u}{M_r} > 1 \) \( \therefore \) unsafe

If the beam section is unsafe, either

a. Change the steel combination and increase the \( A_s \)

b. Increase the section depth \( h \)

Iterate until the economic ratio is less than or equal to 1.

If \( M_U > M_1 \) \( \therefore a > t_s \), therefore Case (II)

![Figure 70 Real T-section where \( a > t_s \)](image)

21. \( A_{s_{total}} = A_{s1} + A_{s2} \)

22. \( M_2 = cy_{ct} = 0.45 F_{cu} (B - b) t_s \left( d - \frac{t_s}{2} \right) \)
23. Calculate $A_{s1}$ given $T = \frac{M_2}{y_{ct}} = \frac{M_2}{d - \frac{r_x}{2}}$ and $T = 0.87 F_y A_{s1}$ \therefore $A_{s1} = \frac{M_2 \times 10^3}{d - \frac{r_x}{2}} 0.87 F_y$

24. $M_3 = M_u - M_2$

25. $R_u = \frac{M_3 \times 10^6}{bd^2}$

26. $\mu_{\text{maximum}}$ is obtained from the $R_u$ tables using
   a. $F_{cu}$: 25, 30, 35, 40
   b. $F_y$: 240, 280, 360, 400, 450

27. $\mu_{\text{computed}}$ is obtained from the $R_u$ tables using
   a. $F_{cu}$: 25, 30, 35, 40
   b. $F_y$: 240, 280, 360, 400, 450
   c. $R_u$: Varies based on $u$

If $\mu_{\text{computed}} \gg \mu_{\text{maximum}}$, then either increase the depth of the section $d$ or add compression steel.

28. $A_{s2} = \mu_{\text{computed}} bd$

29. $\mu_{\text{min}}$
   a. For high tensile steel, $\mu_{\text{min}}$ should be the smallest of $\frac{1.1}{F_y}$ and 0.0015
   b. For mild steel, $\mu_{\text{min}}$ should be the smallest of $1.33 \mu_{\text{comp}}$ and 0.0025

This ensures that ductility and shrinkage do not result in a brittle failure, but in a ductile failure.

30. $A_{s\text{min}} (1) = \mu_{\text{min}} bd$

31. $A_{s\text{min}} (2) = \frac{M_U \times 10^6}{0.87 F_y 0.95 d}$

32. $A_{s\text{calculated}}$ is the largest of $A_{s\text{computed}}$, $A_{s\text{min}} (1)$ and $A_{s\text{min}} (2)$
   a. $A_{s\text{Total}}$
   b. $A_{s\text{min}} (1)$
   c. $A_{s\text{min}} (2)$
33. Using $A_{s, \text{calculated}}$, select the nearest $A_s$ to be $A_{s, \text{actual}}$

34. Check the maximum number of bars $n_{1, \text{row}}$ that fit in one row

a. Select clear cover $cc$

b. Calculate $n$

\[ b = 2cc + 2\varnothing_{\text{stirrups}} + n_{1, \text{row}}\varnothing_{\text{bars}} + (n_{1, \text{row}} - 1) \times \text{Least allowable spacing between bars} \]

\[ \therefore n_{1, \text{row}} = \frac{b - 2xc - 2\varnothing_{\text{stirrups}} + \text{Last allowable spacing between bars}}{\varnothing_{\text{bars}} + \text{Least allowable spacing between bars}} \]

The least allowable spacing between bars is typically 25mm.

c. Round $n_{1, \text{row}}$ down to the nearest integer

**Negative section moment**

The design of the negative section follows the below set of steps:

1. Cover $c$

2. Effective depth $d$

\[ d = h - \text{cover} \]

3. $R_u = \frac{M_u \times 10^6}{bd^2}$

4. $\mu_{\text{maximum}}$ is obtained from the $R_u$ tables using

   a. $F_{\text{cu}} : 25, 30, 35, 40$

   b. $F_{\text{y}} : 240, 280, 360, 400, 450$

5. $\mu_{\text{computed}}$ is obtained from the $R_u$ tables using

   a. $F_{\text{cu}} : 25, 30, 35, 40$

   b. $F_{\text{y}} : 240, 280, 360, 400, 450$

   c. $R_u : \text{Varies based on } \mu$

If $\mu_{\text{computed}} \gg \mu_{\text{maximum}}$, then either increase the depth of the section $d$ or add compression steel.

6. $A_{s, \text{computed}} = \mu_{\text{computed}} bd$
7. \( \mu_{min} \)
   a. For high tensile steel, \( \mu_{min} \) should be the smallest of \( \frac{1.1}{F_y} \) and 0.0015
   b. For mild steel, \( \mu_{min} \) should be the smallest of 1.33\( \mu_{comp} \) and 0.0025

This ensures that ductility and shrinkage do not result in a brittle failure, but in a ductile failure.

8. \( A_{smin\ 1} = \mu_{min} \cdot bd \)

9. \( A_{smin\ 2} = \frac{M_U \times 10^5}{0.87F_y, 0.95d} \)

10. \( A_{scalculated} \) is the largest of \( A_{scomputed} \), \( A_{smin\ 1} \) and \( A_{smin\ 2} \)
    a. \( A_{scomputed} \)
    b. \( A_{smin\ 1} \)
    c. \( A_{smin\ 2} \)

11. Using \( A_{scalculated} \), select the nearest \( A_s \) to be \( A_{sactual} \)

12. Check the maximum number of bars \( n_{1\ row} \) that fit in one row
    a. Select clear cover \( cc \)
    b. Calculate \( n \)

\[
b = 2cc + 2\varnothing_{stirrups} + n_{1\ row}\varnothing_{bars} + (n_{1\ row} - 1)\times Least\ allowable\ spacing\ between\ bars
\]
\[
\therefore n_{1\ row} = \frac{b - 2xc - 2\varnothing_{stirrups} + Least\ allowable\ spacing\ between\ bars}{\varnothing_{bars} + Least\ allowable\ spacing\ between\ bars}
\]

The least allowable spacing between bars is typically 25mm.

    c. Round \( n_{1\ row} \) down to the nearest integer

13. Calculate \( d_{actual} \)
    a. Calculate \( c_{actual} \)
       i. If 1 row: \( c_{actual} = c + \varnothing_{stirrups} + \frac{\varnothing_{bars}}{2} \)
ii. If 2 rows: $c_{\text{actual}} = cc + \emptyset_{\text{stirrups}} + \emptyset_{\text{bars}} + \frac{\text{Least allowable spacing between bars}}{2}$

b. $d_{\text{actual}} = h - c_{\text{actual}}$

14. Calculate $\mu_{\text{actual}}$

$$\mu_{\text{actual}} = \frac{A_{s_{\text{actual}}} (\text{mm}^2) \times 10^2}{bd_{\text{actual}}}$$

15. $R_u$ is obtained from the $R_u$ tables using
   a. $F_{cu}: 25, 30, 35, 40$
   b. $F_y: 240, 280, 360, 400, 450$
   c. $\mu_{\text{actual}}$: Varies based on $R_u$

16. $M_r = \frac{R_u b d_{\text{actual}}}{10^6}$

17. Economy ratio
   a. If $\frac{M_u}{M_r} < 0.9 \therefore \text{uneconomic}$
   b. If $0.9 \leq \frac{M_u}{M_r} < 1 \therefore \text{economic}$
   c. If $\frac{M_u}{M_r} > 1 \therefore \text{unsafe}$

If the beam section is unsafe, either
   a. Change the steel combination and increase the $A_s$
   b. Increase the section depth $h$

**Shear design**

The design of shear for a beam section follows the below set of steps:

1. $Q_U = V - \left(\frac{c_{\text{column}}}{2} + \frac{d}{2}\right) x w$
2. $q_U = \frac{F}{A} = \frac{Q_U x 10^3}{bd}$
3. $q_{U_{\text{max}}} = 0.7 \frac{F_{cu}}{Y_c} \geq 3MPa$
If $q_U \leq q_{u_{max}}$, continue

If $q_U > q_{u_{max}}$, increase dimensions with preference to $h$ to affect moment capacity as well.

4. $q_{cu} = 0.24 \sqrt{\frac{f_{cu}}{\gamma_c}}$

If $q_U \leq q_{cu}$, shear reinforcement is not required, minimum stirrups $\varnothing 8$ to be used with maximum spacing $S = 200mm$.

If $q_U > q_{cu}$, shear reinforcement required, continue

5. $q_{st} = q_U - \frac{q_{cu}}{2}$

$\frac{n_{\text{branc hes}} A_{s_{\text{stirrups}}}}{F_y / \gamma_s} \leq \frac{n_{\text{branc hes}} A_{s_{\text{stirrups}}}}{F_y / \gamma_s}$

6. $q_{st} = \frac{bS}{n_{\text{branc hes}}} \therefore S = \frac{b q_{st}}{n_{\text{branc hes}}}$

7. Number of branches $n_{\text{branc hes}}$ is defined based on the number of loops

<table>
<thead>
<tr>
<th>Number of loops</th>
<th>Number of branches $n_{\text{branc hes}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
</tr>
</tbody>
</table>

8. In shear, use $\varnothing 8, \varnothing 10$ and $\varnothing 12$ with the below specifications

<table>
<thead>
<tr>
<th>Diameter</th>
<th>Steel type</th>
<th>Area of steel $A_{s_{\text{stirrups}}}$ mm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varnothing 8$</td>
<td>Mild steel $F_y = 240, 280$</td>
<td>50.3</td>
</tr>
<tr>
<td>$\varnothing 10$</td>
<td>Mild steel $F_y = 240, 280$</td>
<td>78.5</td>
</tr>
<tr>
<td>$\varnothing 12$</td>
<td>$F_y = 360$</td>
<td>113</td>
</tr>
<tr>
<td>$\varnothing 12$</td>
<td>$F_y = 400$</td>
<td>113</td>
</tr>
</tbody>
</table>

If the shear is high, increase $A_{s_{stirrups}}$ along with the number of loops to resist it.
9. \( S_{\text{minimum}} = 100\text{mm} \)
10. \( S_{\text{maximum}} \) is the smaller of:
   a. \( \frac{d}{2} \)
   b. \( \frac{n_{\text{branc hes}} A_{\text{stirrups}} F_y}{0.4b} \)
   c. \( 200\text{mm} \)
   d. \( \frac{n_{\text{branc hes}} A_{\text{stirrups}}}{0.0015b} \) for mild steel and \( \frac{n_{\text{branc hes}} A_{\text{stirrups}}}{0.001b} \) for high tensile steel
11. \( S_{\text{minimum}} \leq S \leq S_{\text{maximum}} \)
12. Assume \( n_{\text{branc hes}} = 2, \varnothing 8 \rightarrow A_{\text{stirrups}} = 50.3 \)
    \[ n_{\text{branc hes}} A_{\text{stirrups}} \frac{F_y}{\gamma_s} \]
   a. Calculate \( S = \frac{n_{\text{branc hes}} A_{\text{stirrups}} F_y}{bq_{st}} \)
13. If \( S < S_{\text{minimum}} \), assume \( n_{\text{branc hes}} = 2, \varnothing 10 \rightarrow A_{\text{stirrups}} = 78.5 \)
    \[ n_{\text{branc hes}} A_{\text{stirrups}} \frac{F_y}{\gamma_s} \]
   a. Calculate \( S = \frac{n_{\text{branc hes}} A_{\text{stirrups}} F_y}{bq_{st}} \)
   b. If \( S < S_{\text{minimum}} \), assume \( n_{\text{branc hes}} = 4, \varnothing 10 \rightarrow A_{\text{stirrups}} = 78.5 \)
    \[ n_{\text{branc hes}} A_{\text{stirrups}} \frac{F_y}{\gamma_s} \]
   i. Calculate \( S = \frac{n_{\text{branc hes}} A_{\text{stirrups}} F_y}{bq_{st}} \)
14. If \( S > S_{\text{maximum}} \), take \( S = S_{\text{maximum}} \)
15. No. of stirrups/m \( n_{\text{stirrups}} = \frac{1000}{S} \approx \uparrow \text{round up} \)

**Shrinkage bars and stirrup hangers**

- The stirrup lock is placed at the compression side
- Shrinkage bars are taken as \( s_{\text{shrinkage}} = 8\% \text{ of } A_{\text{main reinforcement}} \)
- \( 2\varnothing 10 \)
- The number of rows of the shrinkage bars are determined by the depth of the section has follows:
  - \( h < 60\text{cm} \) – No shrinkage bars required
- $60cm < h < 70cm$ – 1 row of shrinkage bars
- $70cm < h < 100cm$ – 2 rows of shrinkage bars
- $100cm < h < 130cm$ – 3 rows of shrinkage bars

- Stirrup hangers are taken as

\[
A_{\text{stirrup hangers}} = 10\% \, of \, A_{\text{main reinforcement}} \leq \varnothing 10
\]
APPENDIX II – CASE I SAMPLE DESIGN DRAWING
APPENDIX III – CASE II SAMPLE DESIGN DRAWING
Case II: Medium-income affordable house

Before Optimization

<table>
<thead>
<tr>
<th>Type</th>
<th>Notes</th>
<th>Unit Area</th>
<th># Rooms</th>
<th># Bathrooms</th>
<th># Beds</th>
<th># Households</th>
<th># Parking</th>
</tr>
</thead>
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<tr>
<td>A</td>
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<tr>
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<td>2</td>
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<td>2</td>
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<td>2</td>
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</table>

Project Map

Drawing Notes & Revision History

Client
Main Consultant
Sub Consultant

Drawing Reference
Case II: Medium-income affordable house

After Optimization