COST EFFICIENT OPTIMIZATION OF REINFORCED CONCRETE STRUCTURES

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Approval sheet of the Thesis

This is to certify that we have read this thesis entitled **“Cost efficient optimization of reinforced concrete structures”** and that in our opinion it is fully adequate, in scope and quality, as a thesis forthe degree of Master of Science.

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ABSTRACT

COST EFFICIENT OPTIMIZATION OF REINFORCED CONCRETE STRUCTURES

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In Tirana, reinforced concrete (RC) buildings are among the most common types of construction. Nowadays in this high competitive industry, where there is a constant rise in customer demand for better quality, better safety, and lower cost, structural optimization is really needed. The traditional methods of design development heavily rely on expensive material consumption and enormous design margins, which ultimately consumes more material into the construction projects. Computational power has improved in efficiency and accessibility over the past few decades.Because of the high capacity computing power that was available,designers had the chance to use finite element analysis techniques to compare various options even while the design phase was still in progress. A number of sophisticated and original algorithms for simultaneously optimizing a number of design variables while considering the needed constraints and scenarios were also produced as a result of the research efforts. The designers now have countless options for more effective and efficient management of the development thanks to the high power computation and these algorithms.

The optimization of load-bearing RC structures in terms of cost impact is the topic of this paper. The study includes a review of the software tools, procedures, and optimization principles for structural design and analysis. The optimization of an eight story reinforced concrete building structure (RCC) is also covered, using structural analysis software like SCADA PRO and optimization tool like ACE-OCP.

Keywords: *efficiency,reinforced concrete,computational power,optimization, optimizational tool,building structure*

ABSTRAKT

OPTIMIZIMI I STRUKTURAVE BETON-ARME NE EFIKASITET KOSTOJE

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Në Tiranë, ndërtesat e betonit të armuar (RC) janë ndër llojet më të zakonshme të ndërtimit. Në industrinë e sotme me konkurrencë të ashpër, ku ka një rritje të vazhdueshme të kërkesës së klientëve për cilësi superiore, siguri më të mirë dhe kosto të përballueshme, optimizimi strukturor është thelbësor. Metodat tradicionale të zhvillimit të projektimit mbështeten shumë në konsumin e tepruar të materialit dhe marzhet jashtëzakonisht të larta të projektimit, gjë që përfundimisht rezulton në konsumimin e më shumë materialit në struktura dhe ndërtesa. Programet kompjuterike jane përmirësuar në efikasitet dhe aksesueshmëri gjatë dekadave të fundit. Për shkak të programeve kompjuterike me kapacitet të lartë që ishin në dispozicion,projektuesit paten mundësinë të përdorin FEA(finite element analysis) për të krahasuar opsione të ndryshme edhe kur faza e projektimit ishte ende në progres. Përpjekjet kërkimore kontribuan gjithashtu në një numër algoritmesh të sofistikuara dhe krijuese për optimizimin e njëkohshëm të një numri variablash të projektimit duke marrë parasysh një sërë kufizimesh dhe skenarësh. Dizajnerët tani kanë opsione të panumërta për menaxhim më efektiv dhe efikas të zhvillimit falë programeve kompjuterike te zhvilluar dhe këtyre algoritmeve.

Optimizimi i strukturave RC mbajtëse për sa i përket ndikimit të kostos është tema e këtij punimi. Studimi përfshin një rishikim të mjeteve të softuerit, procedurave dhe parimeve të optimizimit për projektimin dhe analizën strukturore. Optimizimi i strukturës së ndërtesave të betonit të armuar shumëkatëshe (RCC) është gjithashtu i trajtuar, duke përdorur si softuerin e analizës strukturore si SCADA PRO po ashtu edhe mjetin e optimizimit si ACE-OCP.

Fjalët kyçe: *Efikasitet ne kosto,optimizim,struktura beton-arme,programe kompjuterike,mjet optimizimi*

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CHAPTER 1

INTRODUCTION

1.1 Research problem/Situation of price increasing in construction in Albania

In Tirana, the trend of rising apartment prices has continued even in the second six months of the year. Real estate experts claim that in the area around the ring and the center, no new building being built has prices lower than 1,500 euros/m2. This year it is noticed that the gap between the prices of apartments in the new buildings being built and the existing ones is high.The prices of apartments in the area around the center have become more expensive by at least 10-15% compared to a year ago.The price increase has happened because of some reasons where some of them are;lack of building permits in the center; increase of infrastructure impact tax up to 8%; added cost by the way the portion given to landowners is calculated; floor lowering; greater compliance with building standards; increasing the tax on profits from the sale of real estate from 10% to 15%, starting from January 1, 2015, etc.On the other hand all the people who live in the Albanian capital for rent want to buy a house but these requests are not finalized with transactions.We can list many reasons why it is not finalized: unemployment, low income, the impossibility of obtaining a loan due to financial instability, etc.In the former Block area, apartment prices in 2020 ranged from 2,500 to 2,700 euros per square meter. This year, from the administrators of the sales offices in the new facilities that are being built in this area, the prices are 3,000 euros per square meter. The increase in prices, according to the sales office, is due to the high cost of the land that has been paid to the owners.There has also been an increase in apartment prices in the area of the former New York University. In the new building where the university was built, the sales prices, according to the sales office, will be 1,700 euros per square meter. In 2020, apartment prices in this area were around 1,400-1,450 euros per square meter.

This year, higher sales prices are also offered by the residential areas which have completed the works. The apartments in the "Lake View" buildings near the artificial lake, this year, according to the sales office, are priced at 2,200 and 2,500 euros per square meter, only for the apartments on the top floors of the building from 1,800 to 2,200 euros per square meter that have been sold in 2020.The tendency is the same for areas far from the center. In the newly completed construction on "Hoxha Tahsim" street, on the border with "Bardhyl" street, according to the sales administrator, the apartment prices are 1,400 euros per square meter. In this area, apartments in 2020 were sold from 1,000 to 1,100 euros per square meter.

The Zirkon complex, which is being built in front of the Pediatric Hospital at the "Mother Teresa" University Hospital Center (QSUT), according to the sales administrator, is selling apartments at prices of 1,000 euros per square meter, while the existing apartments in this area in 2020 were sold at 800 to 900 euros per square meter.In the "5 Maji" area, a builder claimed that after three months he would start construction of a new building and the selling prices would be 850 euros per square meter. The same subject said that in the building built in the same area, he sold the apartments at prices of 750 to 800 euros per square meter.So as we can see the prices are going up and up not taking in consideration the economy of the population where the average salary is 400-500 euros.

1.2 Thesis Objectives

- Determine the real situation of price increase in Tirana
- Finding a solution for price decreasing the cost of the construction
- Optimizing the structure design using the software
- Evaluation of the price reduction

1.3 Motivation

Being an architect,critical thinking and skepticism is part of our thinking and lives.On the other side architects are more concerned and sensitive to the surrounding environments in an architectural way.And what would make us more sensitive than the place where we live in,and in this case Albania and in particular the capital city,Tirana are part of me as a young architect.As being the capital city of Albania it would make it the most developed city in different fields including architecture.As being the most developed city it would bring also the most of the problems.And the biggest ones are those who directly affect the population.Considering that Albania has only 32 years that has been out of the communist regime it has left us a little bit behind and nowadays is being built in a massive way to complete the absence of it,in particular in Tirana.Albania's economy is not in good condition which would make also the middle class people having difficulties.One of these people's main concern is housing where I would say home is the heart of every family.The fact is that it is being built a lot but the prices of housing are that high that are far away from the reasonable price.As mentioned above being part of the city as architects and citizens we should always try to find solutions for the community by linking these two parts of ours

1.4 Outline

This thesis is divided in 5 chapters. The organization is done as follows:

In Chapter 1, the research problem for price increasing of construction is presented,motivation why this thesis is started and objective and scope of works. Chapter 2, includes the literature review where different methods and types of structural design optimization are presented.Chapter 3, consists of the methodology used in this study and in Chapter 4, the case study presentation and simulations.Chapter 5,consist of the results and discussions over the simulations done in the previous chapter over the price reduction of the structure.In the end is chapter 6 which consist on the conclusion of the whole master thesis.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Nowadays, structural optimization is a very important tool because it enables engineers and architects to design structures that are both cost-effective and meet performance standards.The reader will learn how everything began and how it is developing day by day by reading this literature review's major research studies, technology developments, methods,new and fundamental techniques.

Significant developments in the field of structural optimization have occurred recently as a result of advancements in computational tools, optimization algorithms, and material science. Researchers and professionals have worked to optimize various structural components, configurations, and materials to increase structural performance, use less material, and have the least negative environmental impact possible. In addition to highlighting the contributions of earlier research studies, this review looks at the existing literature to identify the key trends, challenges, and opportunities in the field of structural optimization.

The review starts out by looking at the basic concept and theory of what structural optimization is.After that a practical example is given so that definition makes sense in real practice.It explores the fundamentals of algorithms,some of the very first achievements for solving optimization problems in construction.And then this review is focused more on solving optimization problems specifically for reinforced concrete structures such as beams and columns

The review also examines a number of optimization goals that are frequently taken into account in structural engineering, including maximizing stiffness, minimizing weight, optimizing environmental impact, and ensuring structural stability.

The optimization of various structural elements, including beams, columns, frames, and shells, as well as optimization algorithms and objectives, are covered in this literature review. It examines modern techniques for enhancing these components, including topology optimization, shape optimization, sizing optimization, and material optimization. These studies findings will be examined to demonstrate the enhancements made in optimizing specific structural components and the benefits in terms of structural efficiency and sustainability that come along with them.

Through a careful review of the literature, this study seeks to consolidate the information and understanding gained from earlier structural optimization research projects. The remaining chapters of this thesis, which conduct case studies and empirical research to advance the field and close gaps in the literature, will build on this chapter as a foundation.

This literature review will conclude by summarizing the most recent advancements, approaches, and expertise in structural optimization in civil engineering. It will give an in-depth comprehension of the current state of the field today, determine areas for further study, and lay the basis for the remaining chapters of this master's thesis, eventually leading to sustainable and optimized structural design methods.

2.2 Fundamentals of Structural Optimization

2.2.1 Definition of Structural Optimization

The architecture, engineering, and construction (AEC) industry consumes a significant amount of resources, so its sustainability and efficiency have come under increasing scrutiny in recent years. According to (Rozvany, 2009),it involves using computational tools and mathematical algorithms to explore various design options and determine the best structural configuration. It has become one of the most well-liked methods for developing durable and efficient designs in the construction world.In order to optimize, some requirements must be met in order to achieve the optimum result. Every phase of a project's life cycle, including design, construction, operation, and maintenance, can be optimized in the field of civil engineering. (Mei, L. and Wang, Q., 2021) state that one of the optimization techniques that is most frequently used is structural optimization.A common characteristic of structural design optimization problems in civil and industrial engineering is the presence of many competing objectives, such as obtaining the lowest investment cost and the highest level of design safety. This dilemma forces these issues to have a set of solutions rather than just one.

These options show the potential trade-offs between the various optimization goals (Zavala et al., 2014). The response of the structure should be acceptable in accordance with numerous parameters, i.e., it should at least be a practicable design, according to (Ghalimath et al., 2018) study. There may be several workable designs, but it is preferable to pick the greatest one out of the available options. The best design could be measured in terms of lowest price, lightest weight, highest performance, or some combination of these.

2.2.2 Optimization problem formulation

According to (Technical Committee on Optimal Structural Design, 1997) the optimization process is a complicated one that comprises various crucial elements that must be considered.By examining the issue of constructing a welded plate girder for a highway bridge, it is step-by-step explained. The girder was to be designed with the smallest possible cross-sectional area.

- *Determination of independent design parameters and their definition*

It is important to recognize and define independent design variables. The first step in the problem formulation phase is to carefully identify and define the variables that describe the system design. The system's design can be determined once the values of these variables are known. Usually, the design variables work independently of one another. In order to have a useful system design, there must be limits on equality between the parameters if some of those that depend are also specified as design parameters.

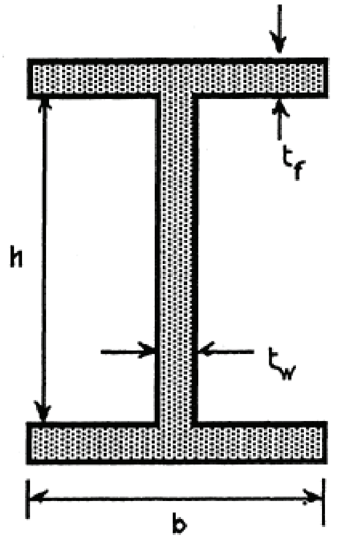


Figure 1. Cross section of plate grider

o At this stage of the issue formulation phase, obtaining all the essential design parameters and data and precisely defining them is also necessary. These include elements like loading conditions and material properties. Any additional problem parameters that directly or indirectly depend on the design variables must also be observed and defined. These variables are referred to as dependent variables and include the cross-sectional properties of members, the bending stress, the stress from shear, deformation, etc.

o Recognizing and outlining an objective function

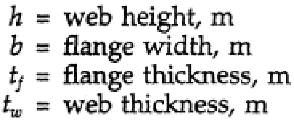
The second step in the problem formulation process is determining and defining the parameters of an objective function that assesses the relative value of alternative designs. For the minimization problem, this objective function is referred to as the price junctions. Either directly or indirectly, this scalar function must be a dependent variable on the design variables. After a design has been defined, it ought to be possible to evaluate this function. Examples of objective functions include the system's unit cost, mass, maximum deformation, moment capacity of a section, natural frequency, and others.

o Defining and identifying constraints.

Every design problem has conditions that must be met, such as those for service, strength, and resource accessibility. Therefore, the final step in the problem formulation phase must be the identification and definition of all system limitations.

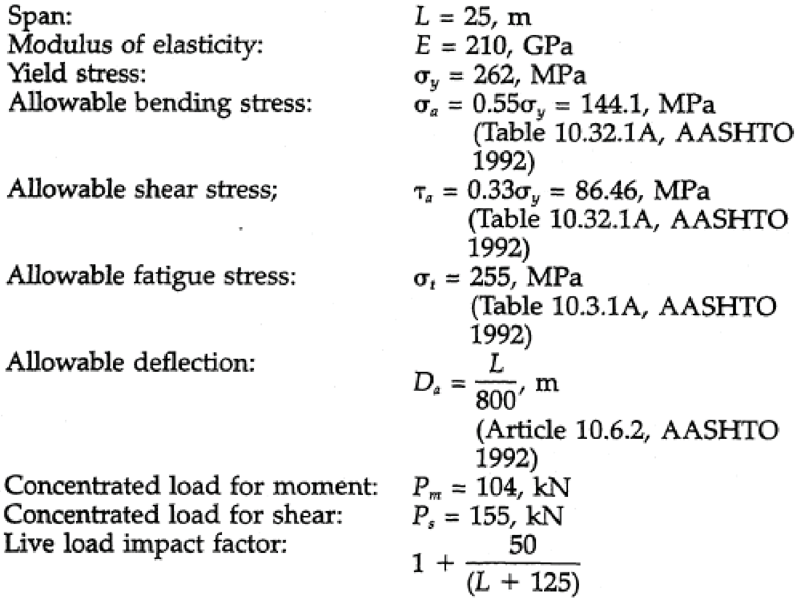
Specific boundaries on the variables as well as the dependent and independent design variables are frequently included in constraint expressions. Quantities like stress, buckling load, natural frequency, and deflection need to be kept to a minimum. An evaluation of the constraint functions requires response analysis of the system for all applied loading instances.

The problem formulation process is shown in the following images below.



h = web height, m
b = flange width, m
t_f = flange thickness, m
t_w = web thickness, m

Figure 2. Design Variables



Span:	$L = 25$, m
Modulus of elasticity:	$E = 210$, GPa
Yield stress:	$\sigma_y = 262$, MPa
Allowable bending stress:	$\sigma_a = 0.55\sigma_y = 144.1$, MPa (Table 10.32.1A, AASHTO 1992)
Allowable shear stress;	$\tau_a = 0.33\sigma_y = 86.46$, MPa (Table 10.32.1A, AASHTO 1992)
Allowable fatigue stress:	$\sigma_t = 255$, MPa (Table 10.3.1A, AASHTO 1992)
Allowable deflection:	$D_a = \frac{L}{800}$, m (Article 10.6.2, AASHTO 1992)
Concentrated load for moment:	$P_m = 104$, kN
Concentrated load for shear:	$P_s = 155$, kN
Live load impact factor:	$1 + \frac{50}{(L + 125)}$

Figure 3. Design Parameters

Cross sectional area: $A = (ht_w + 2bt_f)$, m^2 (1-1)

Moment of inertia: $I = \frac{1}{12} t_w h^3 + \frac{2}{3} bt_f^3 + \frac{1}{2} bt_f h(h + 2t_f)$, m^4 (1-2)

Uniform load: $w = (19 + 77A)$, kN/m (1-3)

Bending moment: $M = \frac{L}{8}(2P_m + wL)$, kN − m (1-4)

Bending stress: $\sigma = \frac{M}{1000I}(0.5h + t_f)$, MPa (1-5)

Flange buckling stress limit: $\sigma_f = 72{,}845 \left(\frac{t_f}{b}\right)^2$, MPa (1-6)

(Article 10.34.2.1.3, AASHTO 1992)

Web crippling stress limit: $\sigma_w = 3{,}648{,}276 \left(\frac{t_w}{h}\right)^2$, MPa (1-7)

(Article 10.34.3.1.1, AASHTO 1992)

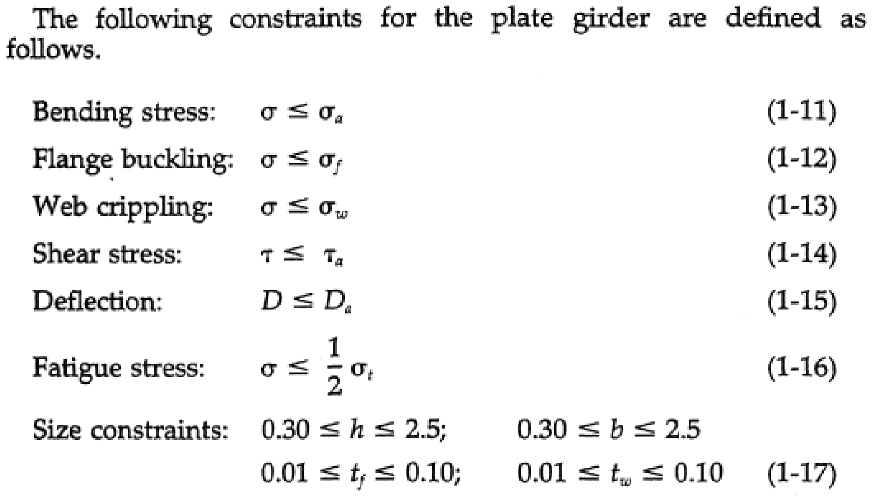
Shear force: $S = 0.5(P_s + wL)$, kN (1-8)

Deflection: $D = \frac{L^3}{384 \times 10^6 EI}(8P_m + 5wL)$, m (1-9)

Average shear stress: $\tau = \frac{S}{1000ht_w}$, MPa (1-10)

Figure 4. Dependent variables

The goal is to reduce the overall mass or, more precisely, its cross-sectional area . As a result, a design that is achievable but has a cross-sectional area that is smaller is said to be a "better design" than one that has a larger area. If these cost factors are known, it is possible to formulate additional cost functions that include the amount spent on costs for materials, production, the welding process, erection, and transport.



The following constraints for the plate girder are defined as follows.

Bending stress: $\sigma \leq \sigma_a$ (1-11)

Flange buckling: $\sigma \leq \sigma_f$ (1-12)

Web crippling: $\sigma \leq \sigma_w$ (1-13)

Shear stress: $\tau \leq \tau_a$ (1-14)

Deflection: $D \leq D_a$ (1-15)

Fatigue stress: $\sigma \leq \frac{1}{2}\sigma_t$ (1-16)

Size constraints: $0.30 \leq h \leq 2.5$; $0.30 \leq b \leq 2.5$
$0.01 \leq t_f \leq 0.10$; $0.01 \leq t_w \leq 0.10$ (1-17)

Figure 5. Constraints

The plate girder design optimization problem is expressed mathematically as follows:

- To reduce the cross sectional area and calculate the design variables h, b, t1, and tw.
- Considering the limitations such as, bending tension, flange buckling, web crippling, deflection, shear stress, and fatigue tension outlined in the equations depicted in the previous images.

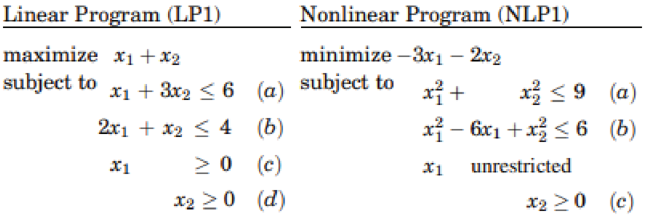
2.3 Concepts and Methodologies in Structural Optimization

2.3.1 Optimization Algorithms and Techniques

Various structural optimization algorithms and methods are used to find the best design solution. Heuristic/metaheuristic methods and traditional optimization techniques can be categorized into two categories.

Nonlinear programming (NLP) and linear programming (LP) are the two main traditional optimization methods. According to (Schulze, 1998) Linear programming is the name of an area of applied math which is concerned with solving certain kinds of optimization problems. When using linear programming, a linear cost function with a specific number of parameters must be minimized or maximized while taking a specific number of limitations into account. The limitations are caused by linear inequalities in each parameter of the cost function. The cost function is commonly referred to as the objective function. Although there are many similarities between linear algebra and linear programming, the main difference between the two is that inequalities are frequently found in the problem statement for linear programming rather than equalities.

The problem on the left is a linear program (LP) because all variables are continuous, including fractional values, inside a given (potentially infinite) period, and the objective function and all restrictions are all linear. While the variables in the right-hand issue are continuous, the objective function or at least one constraint is not, making it a nonlinear program (NLP). You can limit the solution to any area that can be represented in terms of smooth functions using nonlinear constraints. (Solow, 2007).



Linear Program (LP1)

$$\begin{array}{lll} \text{maximize} & x_1 + x_2 & \\ \text{subject to} & x_1 + 3x_2 \leq 6 & (a) \\ & 2x_1 + x_2 \leq 4 & (b) \\ & x_1 \geq 0 & (c) \\ & x_2 \geq 0 & (d) \end{array}$$

Nonlinear Program (NLP1)

$$\begin{array}{lll} \text{minimize} & -3x_1 - 2x_2 & \\ \text{subject to} & x_1^2 + x_2^2 \leq 9 & (a) \\ & x_1^2 - 6x_1 + x_2^2 \leq 6 & (b) \\ & x_1 \quad \text{unrestricted} & \\ & x_2 \geq 0 & (c) \end{array}$$

Figure 6. LP1 and NLP1 functions

Although mathematical programming was initially the most popular technique, other metaheuristic/heuristic techniques have since replaced it (Sánchez et al,. 2012).In contrast to exact approaches, (meta)heuristic methods frequently rely on empirical criteria and have a simple and compact theoretical foundation. (Gavrilas, 2010).These techniques provide strong tools for resolving challenging optimization issues and they are motivated by natural phenomena or problem-solving techniques. These methods include evolutionary algorithms (EA),genetic algorithms (GA), particle swarm optimization (PSO) and simulated annealing (SA),referring to (Coello et al,. 2007).

2.3.2 Early Approaches to Structural Optimization

In accordance with (Ohsaki, 2016),Galileo Galilei is frequently cited as the inventor of structural optimization since he looked into the ideal configuration for a beam under a static stress. His method was largely intuitive, though, and he didn't lay any theoretical groundwork for structural optimization. It is frequently stated that papers by (Michell, 1904) and (Maxwell, 1870) were the first to mention the fundamental concept of topology optimization. (Brandt, 1987) originally published by the Polish Academy of Science, provides a thorough review of the literature on the early developments of structural optimization. It contains more than 1800 entries for the years 1960 to 1980 and more than 300 others up to the 1950s, starting with Galileo Galilei's book. For frames designed in plastic by (Foulkes, 1954)and (Drucker et al,. 1957) optimality conditions were investigated in the 1950s. For a number of structural performance metrics, the 1960s saw the development of conditions or criteria for optimality (Sewell, 1987). (Hu, T. C., & Shield, R. T., 1961)looked into the originality of the best plastic design. (Taylor, 1967) created the ideal condition for a rumbling rod with a specific natural frequency using Hamilton's concept, commonly referred to as the principle of minimum action. (Prager, W. and Taylor, J. E., 1968) developed the optimality criteria for sandwich beams using the minimum total potential energy, Rayleigh's theory, lower- and upperbound theorems of limit analysis, limitations on regulation, natural frequency, buckling load, and plastic limit load. (Prager, 1972) created the optimality conditions for a variety of limitations, such as the case with numerous constraints.

The use of optimality criteria (OC) procedures for finite dimensional structures was common in the 1970s, when computer intelligence was still insufficient to apply methods for mathematically optimizing systems in the real world. (Venkayya V. B., 1973) pioneered the contemporary discrete OC methods to trusses and frames. In order to design trusses, (Dobbs, M. and Nelson, R. B., 1976) created the OC method. (Berke, 1974) and (Venkayya V. B., 1978) both provide reviews of OC methods. Due to the rapid advancement of computer hardware and software technology, many numerical methods were developed in both the 1980s and the 1990s in order to produce the improvement results for practical problems.Numerous works, including (Arora, 2007), (Adeli H. , 1994) and (Haftka et al,. 2012), discuss developments throughout this time period. Additionally, reliability-based design techniques that take into account ambiguities in material properties, loading scenarios, and structural behavior were made possible by breakthroughs in optimization algorithms by (Nowak et al,. 2012).

2.4 Categories of Structural Optimization

Structural optimization has become a vital tool in the design process over the last few decades. The techniques fit into the categories of size,shape,and typology optimization. With respect to a certain amount of material and a particular set of boundary conditions, the optimization may seek to reduce weights,stresses,and compliance. The method can be used to create customized microstructures as well as engineering structures (Salimov, 2022).

(Christensen et al,. 2008) have explained these three methods of optimization very simply and with visual schemes beside text so it can be more understandable.

In this text, x will almost always refer to some kind of structural geometrical part.We categorize structural optimization issues into three classes based on the geometric feature:

- When x is a structural thickness of some kind, such as the cross sections of truss components or the thickness distribution of a sheet, size optimization takes place. Figure 1.2 displays a truss structure's sizing optimization issue.

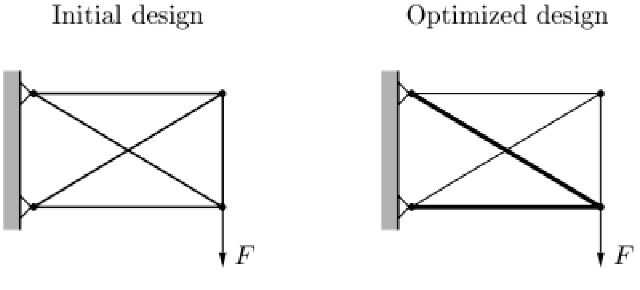


***Figure** 7*. Size optimization

- Shape optimization: Here, x denotes the contour or shape of a specific area of the structural domain's boundary. Take into account how a set of equations based on partial differential equations describes the state of a solid body. The objective of optimization is to choose the way to integrate domain of the differential equations as effectively as possible.Shape optimization does not change the connectivity of the structure by creating new boundaries. Fig. 1.3 depicts a two-dimensional shape optimization issue.

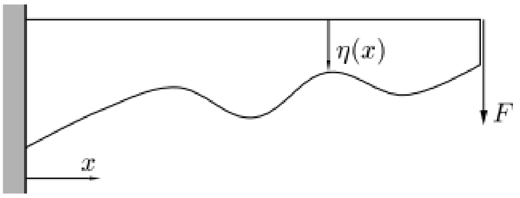


Figure 8. Shape optimization

- Topology optimization is the most versatile kind of structural optimization. In an isolated situation, like for a truss, it is done by using the cross-sectional areas of the truss components as design parameters and then letting these parameters take the value zero, which means removing the bars from the truss. We can say that the topology of the truss changes by changing the connectivity of the nodes in this way (see Fig. 1.4).Topology changes can be made by setting a two-dimensional sheet's thickness to zero when thinking of it as a continuum-type structure as opposed to a discrete structure. If only topological features are optimized, the only possible values for the optimal thickness are 0 and a fixed maximum sheet thickness. In a three-dimensional case, the same outcome can be achieved by changing x into a density-like parameter that can only take the values 0 and 1.A topology optimization example is shown in Figure 1.5. Although in theory shape optimization is a subclass of topology optimization, practical implementations are based on very different methodologies, so the two types are treated differently.The situation is the opposite with regard to the relationship between topology and sizing optimization: from a conceptual standpoint, they are very dissimilar, but from a practical perspective, they are closely related.When the state problem is a differential equation, shape optimization deals with controlling the equation's domain while sizing and topology optimization deals with controlling its parameters.

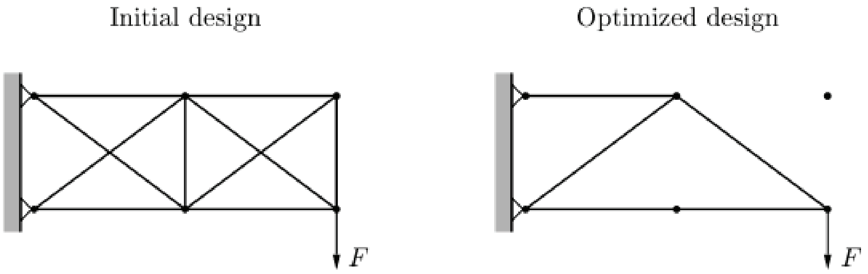


Figure 9. Typology optimization

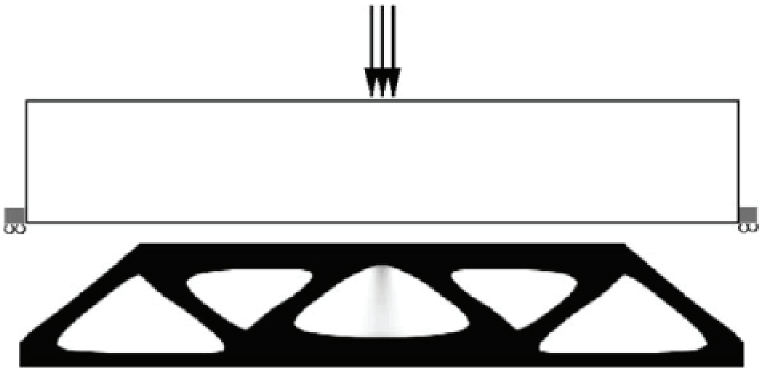


Figure 10. Typology optimization 2

2.5 Objectives of Structural Optimization

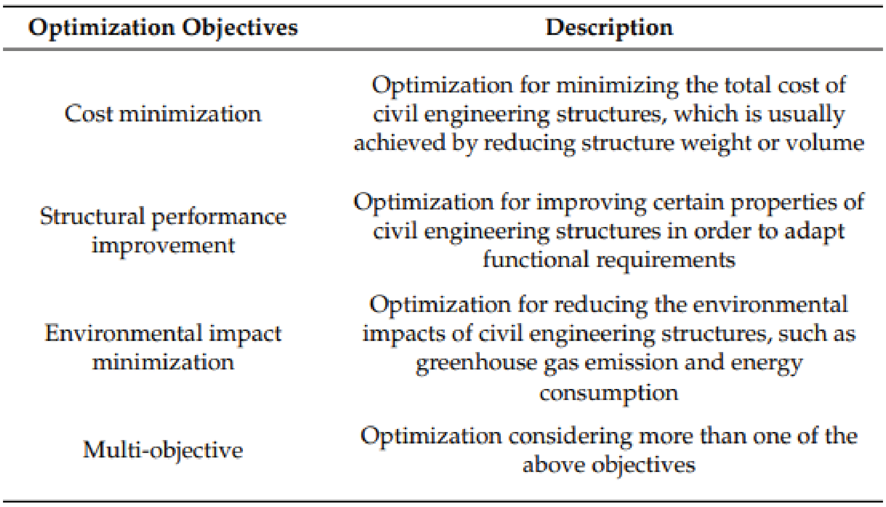
(Mei, L. and Wang, Q., 2021) claim that the following four categories can be used to classify the optimization objectives of the chosen papers based on structural optimization:

- Cost minimization: The objective of structural optimization design is to lower overall costs, which is frequently accomplished by reducing the volume or weight of the structure;

- Structural performance improvement: Enhancing certain structural properties, such as mechanical properties, aerodynamic achievement, and dynamic seismic stability, is the aim of structural optimization design in order to meet environmental needs;

- Minimizing environmental impact: The objective of the structural optimization design is to improve the environmental performance of the structure by reducing greenhouse gas emissions or energy consumption;

- Multi-objective: More than one of the three aforementioned objectives can be found in the structural optimization objective.Following figure summarizes the four optimization objective categories.



Optimization Objectives	Description
Cost minimization	Optimization for minimizing the total cost of civil engineering structures, which is usually achieved by reducing structure weight or volume
Structural performance improvement	Optimization for improving certain properties of civil engineering structures in order to adapt functional requirements
Environmental impact minimization	Optimization for reducing the environmental impacts of civil engineering structures, such as greenhouse gas emission and energy consumption
Multi-objective	Optimization considering more than one of the above objectives

Figure 11. Optimization objectives

2.6 Cost efficient optimization of reinforced concrete structures(beams and columns)

There are many papers published about optimiziation of reinforced concrete structures such as bridges,shear walls,water tanks,slabs etc but this chapter will be focused only on beams and columns since that is what the study will be based on.

2.6.1 Early approaches in concrete beams optimization

Six cost parameters, including the price of concrete, reinforcing steel, prestressing steel,shear steel,formwork,and fiber in concrete,can be used to express the overall expense function for beams.

Based on the ACI code, (Goble, G. G. and Lapay, W. S., 1971) reduce the cost of posttensioned prestressed concrete T-section beams. The first four terms of cost, which are, are included in the cost function. They claim that variations in the cost coefficient don't appear to have an impact on the optimal design.

According to limitations on the tension, prestressing pressure, and vertical coordinates of the tendon, (Kirsch, 1972) shows the lowest cost design of continuous two-span prestressed beams made of concrete by roughly simplifying the nonlinear optimization problem and solving the simplified linear problem using the method of linear programming. In his cost function, he only accounts for the first and third terms of expenses.

Using the ACI code's ultimate moment restrictions, (Friel, 1974) discovers closed-form solutions for the optimum steel to concrete ratio for easily supported, rectangular reinforced concrete beams at a minimal cost. Along with the cost of raising building height, all other costs are taken into account in the cost function. The author comes to the conclusion that the ideal cost is relatively unaffected by the price of formwork and the height increase.

(Naaman, 1976) compares minimal weight and least cost designs for one-way slabs and simply supported rectangular prestressed beams.The first,third and fourth cost parameters are included in the cost function, which is then optimized using a direct search method (Siddall, 1972).The author discovers that minimal weight and minimum cost methods only generate results that are roughly comparable when the ratio of the cost of concrete per cubic yard to the cost of prestressing steel per pound is greater than 60.Otherwise, the minimal cost strategy produces a more economical result, while the cost minimization approach produces significantly more saving results for ratios considerably smaller than 60. The author also notes that the aforementioned ratio is typically less than 60 for US projects.

Using a cost function that's made up only of the first two terms in the cost parameters, (Kirsch, 1983) presents a reduced three-level iterative approach to cost-efficient design of multi-span continuous RC beams with rectangular cross-sections. In each significant area of the first level, the required amount of reinforcement is present based on specific concrete dimensions and design moments. The concrete dimensions of every element are found at the next level. Design moments are optimized at level three. However, the author neglects the real-world limitations of a concrete design code.

According to the restrict state standards of the Indian code, (Prakash et al,. 1988) describe the cost-effective design of single and double reinforced rectangular and T-shape RC beams using Lagrangian and complicated methods. The cost function contains the first two terms from the cost parameters. They claim that a two-way slab is less expensive than the use of a T-beam floor for covers as long as six meters in an apartment type building, however the contrary is true for larger loads with larger spans.

With four variables—steel material, the area of bending reinforcing bars, and beam length and depth, (Ezeldin, 1991) shows the lowest possible expense design of rectangular reinforced fiber concrete beams. The improvement process makes use of direct exploration. (Ezeldin, A. S. and Hsu, C. T. T., 1993) developed the minimal cost design of rectangular, reinforced fiber concrete beams with the addition of the cross-sectional area and stirrup distance, including the cost of shear reinforcement into the cost function. They find that price changes in the material and the shape seem to have a greater impact on the minimal cost than price changes in fibers and reinforcement made of steel.

The general issues surrounding the multilayer optimization of structures are covered by (Kirsch, 1997).A more straightforward statement of the optimization issue is offered together with its mathematical structure. A two-stage design process for prestressed concrete beams is created, with the first level optimizing the prestressing force and tendon coordinates and the second level choosing the concrete dimensions. It is demonstrated that a linear programming form can be used to formulate the first-level problem, enabling a quick and straightforward resolution. In addition, a straightforward explicit nonlinear programming issue can be solved to get the minimal concrete dimensions. The design process described requires resolving a number of straightforward sub-problems.

2.6.2 Cost optimization of concrete beams

(Adeli H. a., 2006) have expressed in the following form the general cost function for prestressed, fiber, or reinforced concrete beams:

$$C_{\mathrm{m}} = C_{\mathrm{cb}} + C_{\mathrm{sb}} + C_{\mathrm{pb}} + C_{\mathrm{fb}} + C_{\mathrm{sbv}} + C_{\mathrm{fib}}$$

Figure 12. Cost function for beams

In this function Cm represents the entire cost of the materials which is the sum of expense for rebars,concrete,formwork,shear steel,prestressing steel and fiber in concrete.On the other hand this equation is expressed differently for a pretensioned beam which can be written as:

$$\begin{aligned} C_{\mathrm{m}} = {} & w_{\mathrm{c}} L_{\mathrm{b}} \left(A_{\mathrm{cb}} - A_{\mathrm{sb}} - A'_{\mathrm{sb}} - A_{\mathrm{pb}} \right) c_{\mathrm{c}} + w_{\mathrm{s}} L_{\mathrm{b}} \left(A_{\mathrm{sb}} + A'_{\mathrm{sb}} \right) c_{\mathrm{s}} \\ & + w_{\mathrm{p}} L_{\mathrm{b}} A_{\mathrm{pb}} c_{\mathrm{p}} + L_{\mathrm{b}} p_{\mathrm{fb}} c_{\mathrm{f}} + C_{\mathrm{sbv}} + C_{\mathrm{fib}} \end{aligned}$$

Figure 13. Detailed cost function for beams

where Lb is the length of the beam,w corresponds to unit weights,c shows the unit cost and A is the cross sectional area.As for the subscripts b stands for beam,c stands for concrete,p stands for prestressing,f stands for formwork and s stands for steel.There are some cases where some of the variables take value 0 because those materials are not included in a specific beam.

2.6.3 Early approaches in concrete columns optimization

The same way as it is done in concrete beams it is applied for concrete columns but the general cost function changes a little bit because of the live cost parameters which are: (1) concrete cost, (2) reinforcing steel cost, (3) prestressing steel cost, (4) formwork cost, and (5) lateral ties cost.

(Ahmed, 1985) created a computer program for the biaxial bending of short reinforced concrete columns at the lowest possible cost. The program needs as inputs the maximum and minimum side lengths of the cross-section, the diameters of the rebars, the ultimate normal force and moments, the material properties of the steel and concrete, the number of longitudinal bars on each side of the cross-section, and the unite price of materials and labor. The program use the sequential unconstrained minimization technique to generate the ideal design variables (side lengths of the cross-section and steel bar diameters), which minimize the cost function using all cost factors except the third cost parameter. Strength, limits on column sides, diameters of the rebars, and the ratio of their area to concrete sectional area are the restrictions. Numerous findings from parametric research were reached.

Short concrete columns subject to uniaxial bending can be designed directly iteratively, according to (Yen, 1990). The limitations are based on ACI strength restrictions. The steel ratio and the placement of the neutral axis are the design factors. The author applies Newton's approach to get the best steel ratio for a column with the specified dimensions and the necessary axial and bending strength.

Following the Australian code, (Kanagasundaram and Karihaloo 1990, 1991) offer the most affordable design for rectangular reinforced concrete columns that are tested with axial compressive force and single or biaxial bending. Sequential LP(linear programming) and Sequential Convex Programming techniques are used to accomplish this.It is taken into account the slenderness ratio of short and long columns. All cost factors are included in the cost function, however the prestressing cost is not. Taylor's series expansions can approximate the goal function and constraints. In a later article, (Kanagasundaram, S. and Karihaloo, B. L., 1991)included concrete strength to the list of design factors along with cross sectional sizes and longitudinal reinforcement area.(Zielinski et al,. 1995) demonstrate cost reduction of RC short tied rectangular columns according on the Canadian code using the internal penalty function technique. The cost function includes the first, second, and fourth cost parameters.

The economic effectiveness of employing high-strength concrete is examined by (Moreno, 1998).The "COLO" computer application is used to carry out the economic evaluation. With the help of this application, multistory building columns and footings are analyzed, designed, optimized, and priced. Based on the idea that the most affordable column has a minimal continuous cross-sectional area and a minimum percentage of reinforcement as defined by the maximum concrete strength utilized for the column, the program can reduce the cost of columns. The program provides the smallest square column size and the weakest concrete strength required to provide the column's given percentage of reinforcement. The parametric analysis demonstrates that the column coat is lower the stronger the concrete is. Additionally, the cost of the column is cheaper with less reinforcement.

2.6.4 Cost optimization of concrete columns

(Adeli et al,. 2006) have done the same thing for expressing the general cost function for a concrete column as they have done with the beams:The following function is showed below:

$$C_{\mathrm{m}} = C_{\mathrm{cc}} + C_{\mathrm{sc}} + C_{\mathrm{pc}} + C_{\mathrm{fc}} + C_{\mathrm{tc}}$$

Figure 14. Cost function for columns

where in this function the total cost is the sum cost for concrete, reinforcing steel, prestressing steel, formwork and lateral ties in.The equation changes for pre-tensioned columns, and it can be written as:

$$\begin{aligned} C_{\mathrm{m}} = {} & w_{\mathrm{c}} H_{\mathrm{c}} \left(A_{\mathrm{cc}} - A_{\mathrm{sc}} - A_{\mathrm{pc}}\right) c_{\mathrm{c}} + w_{\mathrm{s}} H_{\mathrm{c}} A_{\mathrm{sc}} c_{\mathrm{s}} + w_{\mathrm{p}} H_{\mathrm{c}} A_{\mathrm{pc}} c_{\mathrm{p}} \\ & + H_{\mathrm{c}} p_{\mathrm{fc}} c_{\mathrm{f}} + V_{\mathrm{tc}} c_{\mathrm{s}} \end{aligned}$$

Figure 15. Detailed cost function for columns

where Hc shows the height of the column, Acc stands for cross-sectional area of the column, Asc for cross-sectional area of the rebars, Apc for cross-sectional area of the prestressing steel, pfc is the cross-sectional perimeter of the shape, and Vtc is the volume of the ties.

2.7 Example Case study

In this case study it is used evolutionary algorithm where (Kulkarni, A. R. and Bhusare, V., 2016) designed, optimized, and analyzed a multi-story building. The optimization strategy for the case under investigation involved identifying the parameters, creating a equation for the cost function and then determining the optimal set of control parameters to achieve the building's target cost. For the optimization study, a residential building which has 12 floors is taken into consideration.The 3D building model is shown in the following figure.

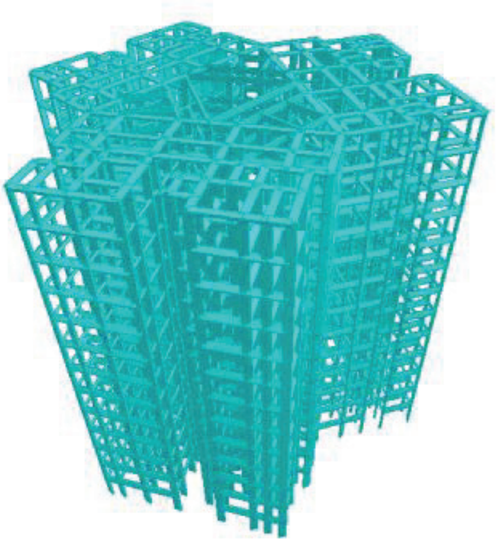
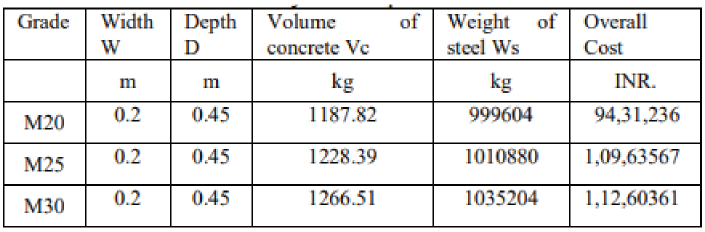


Figure 16. Example Case study 3D model

In this case the authors have considered as the design variables the sizes of beams and columns in three different scenarios because of the concrete grades that will be used in the functions which are M20,M25 and M30.The sizes of beams and columns that are considered as the parameters of the function are expressed as the width and depth.

As it was mentioned above the evolutionary algorithm was used in this case study on this function and with the constraints of width and depth the best solution for each scenario of concrete grade was achieved.The objective was to achieve the most cost effective scenario for this building.These results are shown in the following figure as it follows:



Grade	Width W	Depth D	Volume of concrete Vc	Weight of steel Ws	Overall Cost
	m	m	kg	kg	INR.
M20	0.2	0.45	1187.82	999604	94,31,236
M25	0.2	0.45	1228.39	1010880	1,09,63567
M30	0.2	0.45	1266.51	1035204	1,12,60361

Figure 17. Optimization results for the example case study

As we can see from the figure the best solutions achieved from this study results the first scenario with a concrete grade M20 and following with the parameters results where the depth is 45 cm and the width 20 cm.

CHAPTER 3

METHODOLOGY

The objective of this paper is to lower the project's cost by optimizing concrete structures in a way that is both economical and efficient, as was previously mentioned. This is achieved by lowering the structure's weight, which will lower the demand for materials and, as a result, lower the cost, using optimization techniques based on mechanics and mathematics principles.

3.1 Problem statement and objectives

In civil engineering and architecture, structural optimization is becoming more and more useful.Cost-saving measures during building construction are becoming more and more important due to rising labor and material costs.In Tirana, the price increase is also a result of tax increases that have caused construction costs to soar by 100% in recent years.Albanian construction technology methods, including the machines and materials utilized, are not very advanced, which in turn increases construction time and directly impacts cost. This is not an issue that belongs to architects and engineers; rather, it has to do with the investment made by construction companies.We can make a difference in the design process by producing structures at a lower cost than the initial design that may be suggested.

Notwithstanding everything else, a building's stability and safety are vital aspects of its construction.The first goal is to create a three-dimensional model that complies with all requirements of Eurocode 8, the code for building earthquake-resistant structures. This means that the model will take seismic activity into account.Reducing construction costs is the next and most crucial goal for this study after the completion of the 3D model.

The time factor is something that most designers overlook when optimizing their designs.An optimized structure may have too many outputs given the function's constraints and variables.The more constraints removed, the more optimized the result will be. However, how will those structures perform in terms of labor costs and time in the real world?An illustration of this might be that, although an optimized result might be the most economical in terms of materials, it would require more laborers to put in longer hours, which would raise the overall cost.The factors and limitations taken into account in order to create the most efficient design for this study will be covered in detail in the following subsection.

At the end of the study an evaluation of the results will be done to understand more based on the percentage that will be saved if it would be reasonable to take this process into account or would it be too much time consuming based on the saved cost.

3.2 Optimization Algorithm Selection (Deterministic vs Probabilistic)

There are many optimization techniques used today, many of which are based on earlier studies that are mentioned in the literature review chapter.In the construction industry, probabilistic and deterministic methods are the two most commonly utilized approaches.The world is moving away from deterministic methods and toward probabilistic ones these days.Why does that occur?

While probabilistic approaches offer a greater range of options, deterministic approaches function under set assumptions and produce specific outputs given specific inputs.Instead of focusing on a single definition, the probabilistic method deals with probabilities that offer a wider range of possible outcomes.By being aware of how these techniques operate, designers, architects, engineers, and the like can determine which approach best fits their designs.

A reinforced concrete structure—which is actually based on a building that was built in Tirana, Albania, a few years ago—is the subject of this thesis.It indicates that the building's design has already been completed.The heights, distances, and dimensions of the members (beams and columns).Thus, this leads us to the deterministic optimization technique.Although the probabilistic approach is excellent, it requires that the design be started from scratch, which is not the case.

This method of design is chosen for the reason so the architect can help the engineer through the process.It means after the engineer has finished his constructive model meeting the architects need too,it can go through this optimization process.

3.3 Design Variables and Constraints

These 2 parameters are very crucial for an optimization process to take place because in fact are those 2 parameters that define the inputs and outputs of the whole process.

3.3.1 Design Variables

From one project to the next, these design variables vary depending on the design process.Let us examine the first one, which is the parameters that are geometric.The dimensions of the structural design elements, such as the beams, columns, footings, etc., are known as the geometric parameters.These study parameters are derived from an already-constructed structure.This increases the study's dependability and brings it closer to practical solutions.

The design members who will undergo optimization are among the additional variables taken into account.There are too many members in the construction world such as footings,beams,columns,slabs,walls and many others.Based on their percentage of the structure, the two most used variables—beams and columns—will be used in this study. The more variables added, the more opportunities there are to save money on each of these members, but the more time consuming it will be.For the sole reason that practically all buildings in Albania are constructed using brick slabs, slabs are not taken into consideration.The steel reinforcement's dimensions, which range from 12 to 24 mm, are another crucial factor.

The material properties that will be used in this study is concrete and steel reinforcement.Those materials offer a variety of choose in the construction world based on the needs,strength,cost and many other constraints.

The loads also play a crucial role.Based on what loads are assigned to the model the analyses are affected and so the durability of the model.

3.3.2 Constraints

There are certain requirements that must be met for an optimization process to be applied.The safety and durability of the structure that complies with Eurocode 8 regulations is the first constraint taken into account, as was discussed in the previous subchapter. The analysis that will be done will also be compliant with Eurocode 8.Flexural strength, shear strength, axial compression strength, torsional strength, deflection limits, and other limitations are a few of these limitations.

Budget constraints are typically taken into consideration when designing, but in this case there won't be one because the study is only being done at the study level, and the least expensive option will be selected in the end.

For concrete and steel, respectively, the material properties that will be used in this study are C20-25 and BC500.Since these are the materials utilized in the case study, the investigation will not concentrate on altering the material's characteristics as this would complicate optimization and have an immediate impact on the time and techniques employed on the building site.

The loads that will be taken into consideration for this building will be dead loads.

3.4 Software Application (SCADA PRO)

A platform for determining the best real-world design for civil structural systems is provided by the ACE OCP plugin which is part of SCADA PRO software.It includes all building materials supported by CSi products, including reinforced concrete, steel, aluminum, etc.The 3D model will be modelled through SCADA PRO which is the software that includes the optimization tool which is ACE OCP. As a case study, a reinforced concrete structure will be used which variables are taken by an existing building and there will be a comparison between the current cost and the improved one following the simulations that will be performed on the existing structure.The figure below shows in a graphical relation between the existing design and how the optimization occurs.

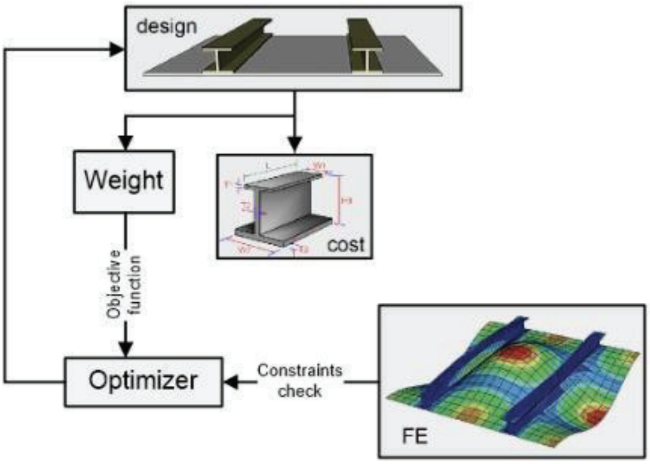


Figure 18. Optimization diagram

There are two different objectives that the optimizing tool achieves to minimize during the process which are the material cost and construction cost.

The term "Material Cost" refers to the price of the materials used to build the structural system under investigation. The cost of concrete plus the cost of reinforcement are added up for RC structures.

Construction Cost: refers to the price associated with building the structural system under study where the cost of labor is taken into account in addition to the cost of materials. There are two distinct differences between labor and material costs. Both types of expenses are deductible and both go into producing a good for consumers. Both expenses are calculated as part of the budgeting procedure and are typically taken into account when deciding how much to charge for the finished product. The unit costs provided in the productivity tab, where the user enters the productivity rates for three groups of elements (beams, columns, and slabs), are used to calculate the labor cost. The productivity rates refer to the amount of time needed to construct a unit volume or weight of concrete, construction steel, steel for reinforcing steel, or aluminum. For each group of elements (beams, columns, and slabs), the labor cost is calculated by multiplying the volume of concrete by the corresponding productivity rate, the weight of reinforcement by the corresponding productivity rate, and the weight of the structural steel for this type of element by the corresponding productivity rate. The working time (hours) is then multiplied by this number, which represents the labor unit cost (currency/h).

CHAPTER 4

CASE STUDY SIMULATION

4.1 Case study presentation and 3D modelling

The building is located at Komuna e Parisit and is constructed in 2008.It's construction is reinforced concrete structure and while modelling the following general information were taken into consideration:

- The residential building consist of 8 floors where the 2 last floors area of the building is smaller than the other floors.In addition to that there is an underground floor which is used for parking purpose.In the modelling structure the last two floors which are mostly terraces will not be taken into consideration.
- The area of the floors up to the sixth floor is 647.7 m2 and tha last two floors's area is 431 m2.
- The general use of the building is for the residential purpose only except the underground floor which is used for parging use as already mentioned and the ground floor which is used for commercial purpose.
- The floors heights goes 3.3 m for the underground level,4.2 m for the ground level and 2.93 m for the rest of the floors.In the modelling structure it will be used the 3.3 m standard height
- The columns distances varies from 4 to 6 m.The shape that is used is rectangular except only one column which is circular shape.
- The slabs are brick slabs so the study will be focused only on columns and beams.
- Beams that are used are flat beams which means their height is 30 cm.
- The concrete material used are C16-20 and C20-25.C20-25 grade concrete is used in the underground level and ground level columns.For the rest of the other

level columns and all the beams is used C16-20 concrete grade.

The following figures are drawings of the building so it can be more understandable.

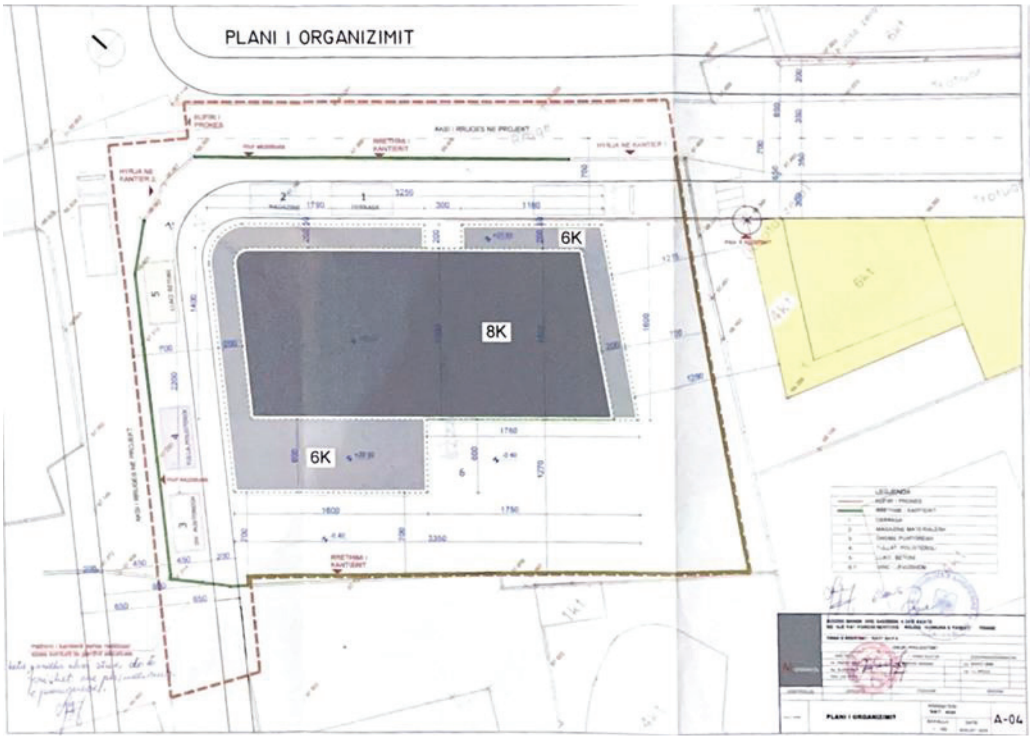
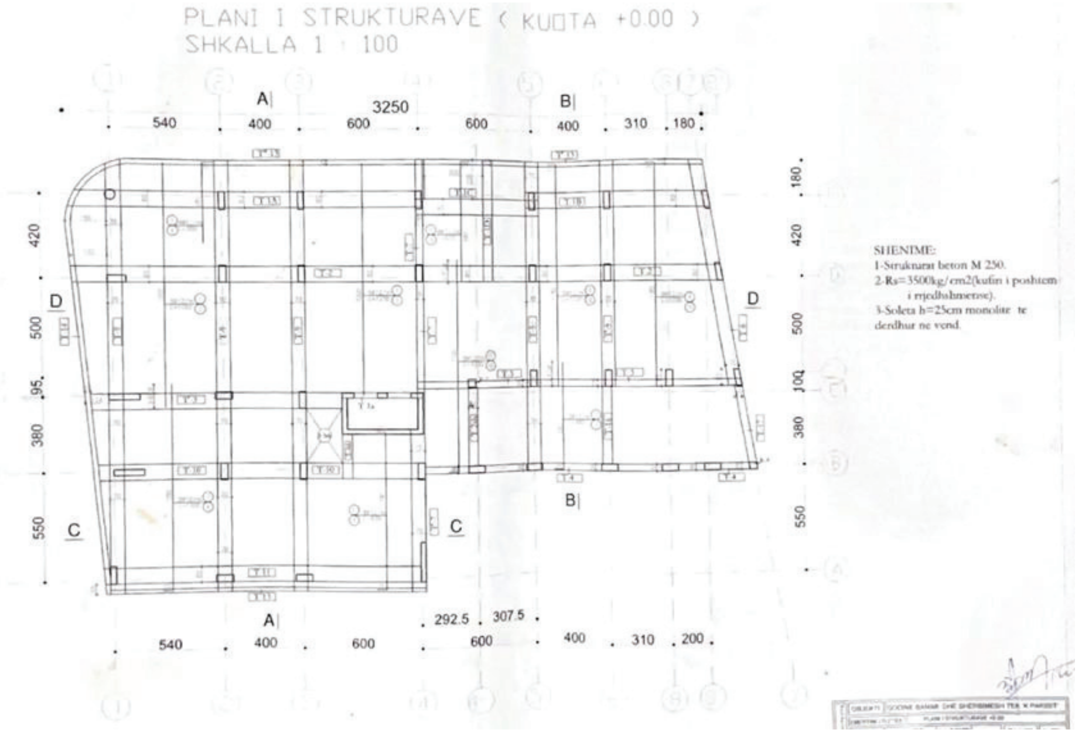


Figure 19. Building Masterplan

Figure 20.Ground floor level

Figure 21. Building fasade



SHENIME:
1-Strukturat beton M 250.
2-Rs=3500kg/cm2(kufiri i poshtem i rrjedhshmerise).
3-Soleta h=25cm monolite te derdhur ne vend.

Figure 22.Strucural plan at level +0.00

The structure will be modelled and analyzed through the SCADA PRO software based on the informations of the case study presented.There will be some changes compared to the original building in geometry.The case study building goes up to 8 floor meanwhile the building that will be used in this study goes up to 6 floor.Also the left part and the right part of the building where the beams are inclined will be removed and the final structure will have an L shape.The rest of it will remain the same such as the building beams and columns dimensions and distances.In the following pictures will be shown a plan of the structure and a 3d modelled one for a better understanding.

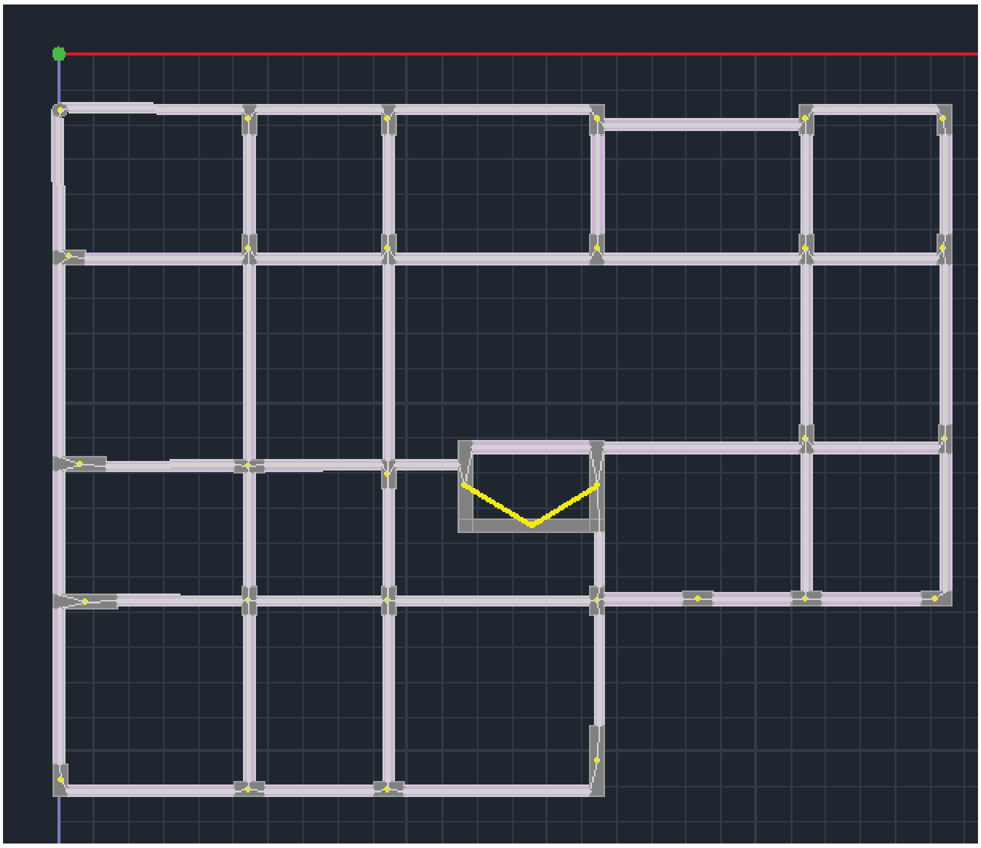


Figure 23.Structural plan of modelled structure

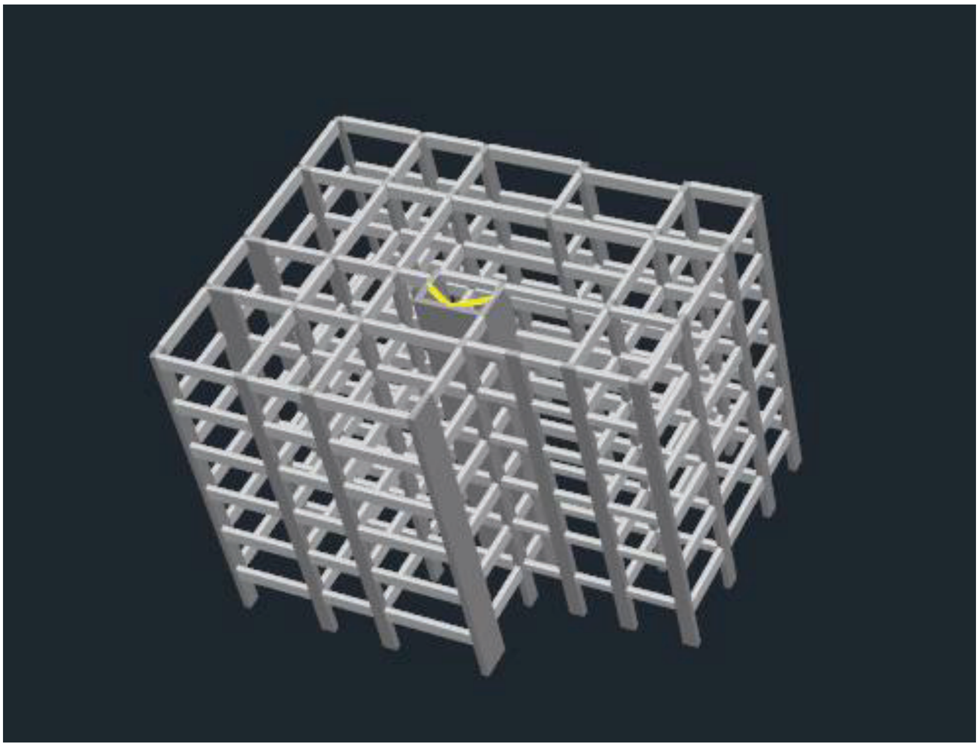


Figure 24.3d view of modelled structure

After the physical model is completed the mathematical model should be created in order that the model can be ready for the analysis to run.

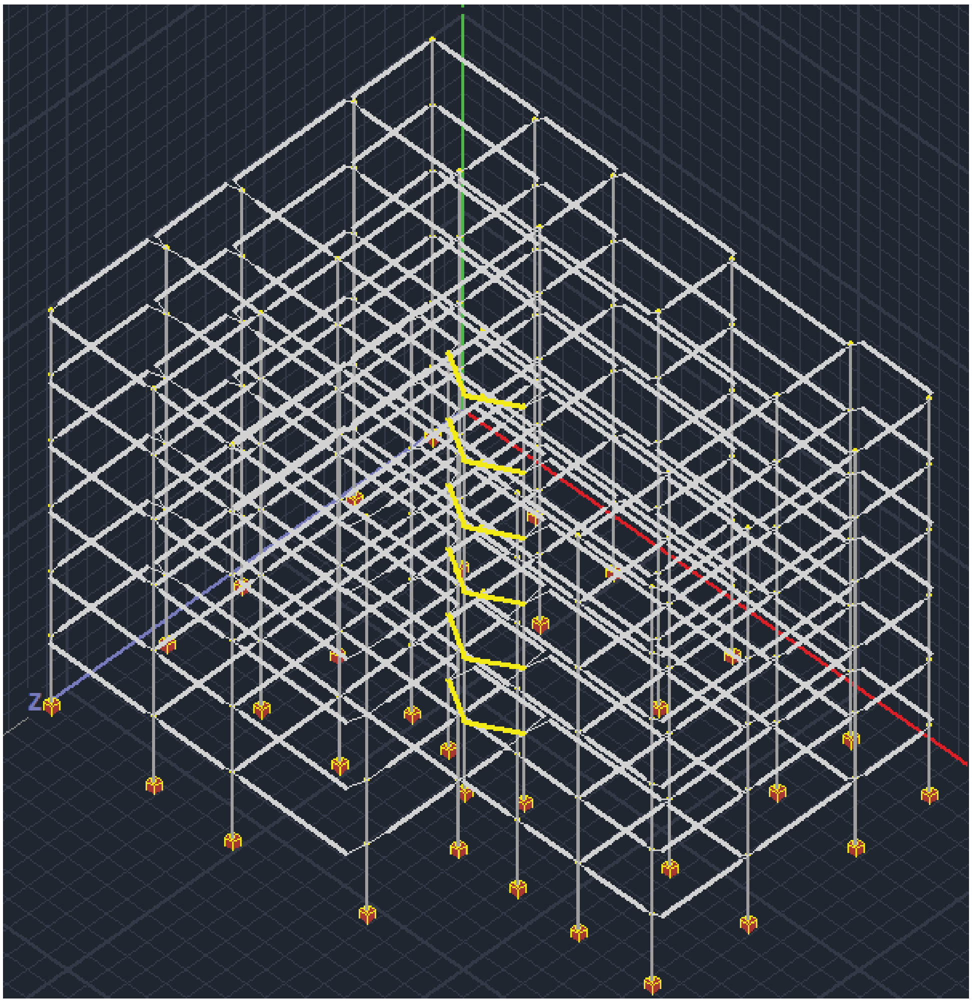


Figure 25. 3d view of mathematical model

As we can see in order for a model to be successfully created all the mathematical members should be connected with each other.Since no footings will be taken into consideration in this study,in the bottom of the structure we can se some small boxes.Those boxes means that the nodes in the end are fixed and it will not cause any problems during analysis.After this process is finished the loads are assigned to the building and the analysis run according to EC-8.After all these processes take place there is one last process and very important one before going to the optimization process and that is member design check.This means that the dimensions of concrete members and the amount of rebars used should be accurate and fulfilling the EC-8.In the following figure an example of faling design members will be provided for a better understanding.

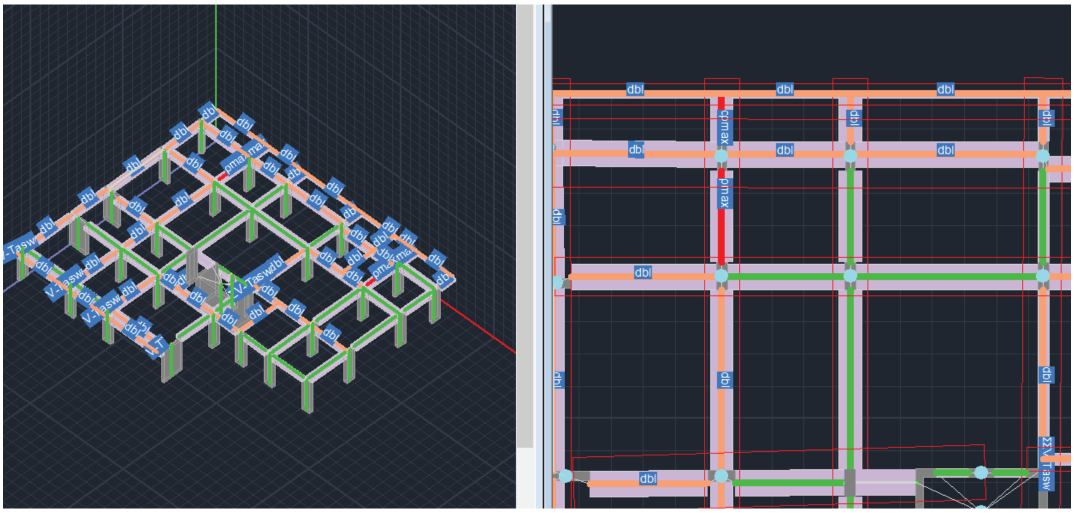


Figure 26. Failing member design example

From the figure we see three different colors.The green one defines that the member design is correctly created,the red one means that the maximum steel reinforcement has been exceeded and the orange one means that the maximum anchorage length has been exceeded.The good thing this software provides is that it can not let you use the optimization process without fixing the structure and making it stable.

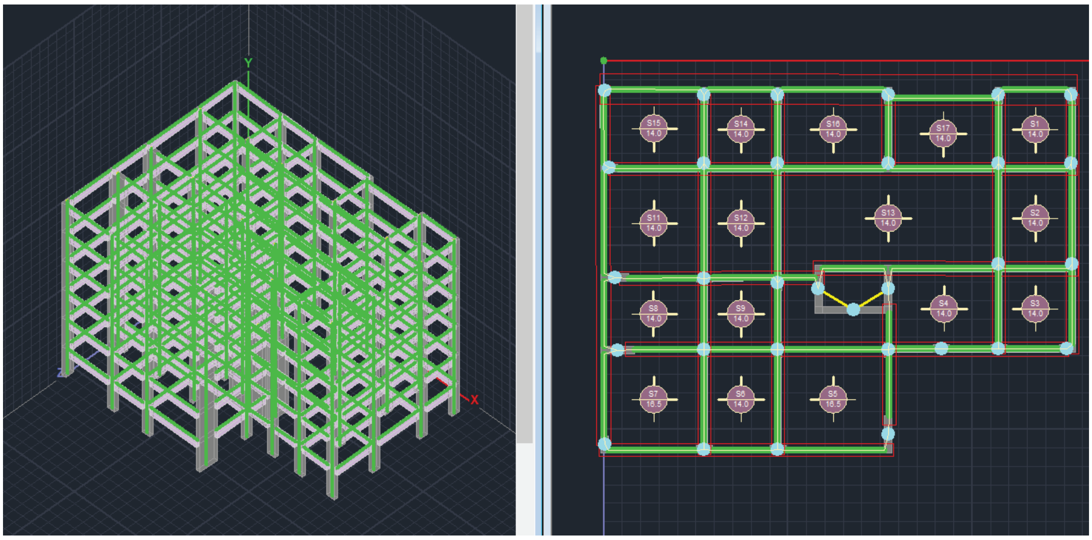
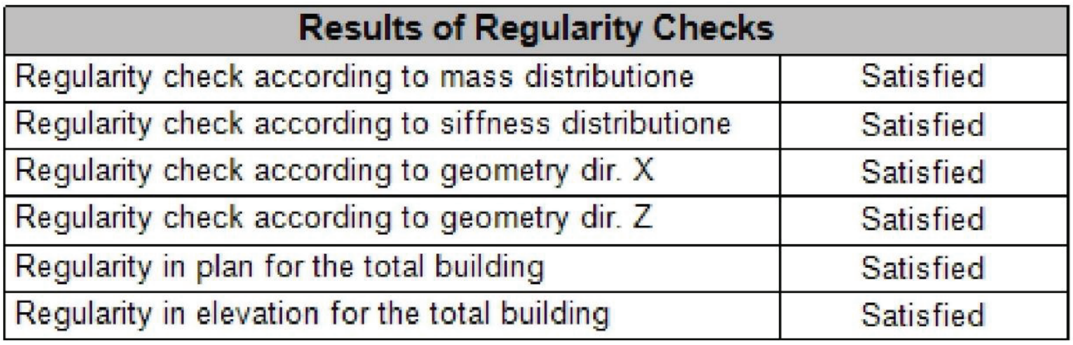


Figure 27. Member design check



Results of Regularity Checks	
Regularity check according to mass distributione	Satisfied
Regularity check according to siffness distributione	Satisfied
Regularity check according to geometry dir. X	Satisfied
Regularity check according to geometry dir. Z	Satisfied
Regularity in plan for the total building	Satisfied
Regularity in elevation for the total building	Satisfied

Figure 28. Results of regularity checks

After the member design check is completed it means the structure is stable and ready to go through optimization process.Before that,let s explain more in detail about the dimensions and positions of every member design (columns and beams).

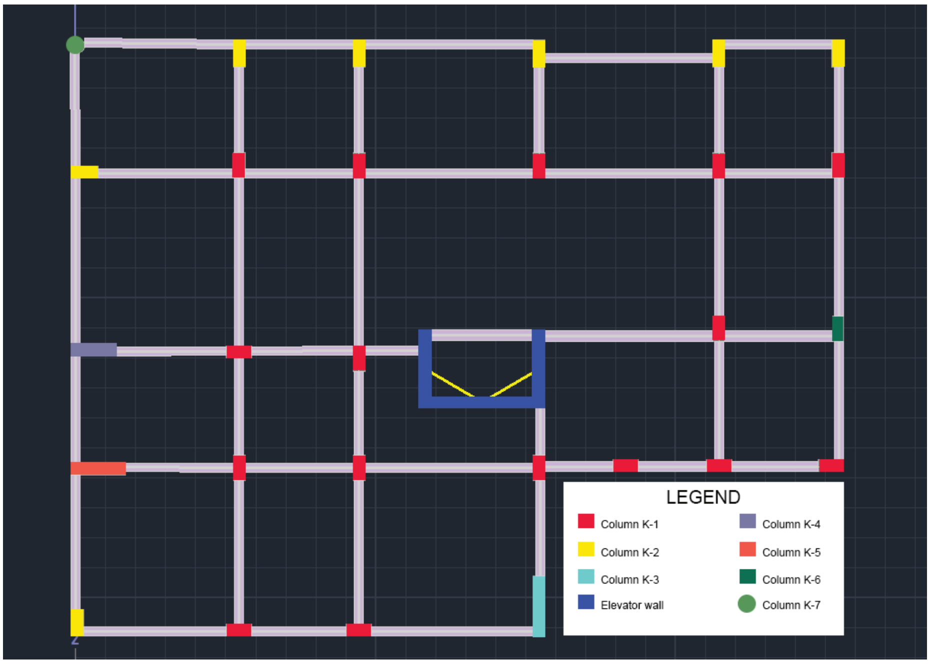


Figure 29. Columns positioning

As it is seen in this legend organization of columns most of the columns that make the structure are columns K-1.After columns K-1,columns K-2 are following according to the highest number and then the rest which are used only once.

Table 1. Dimension of columns

Column Name	**Width dimension**	**Height dimension**
Column K-1	40 cm	85 cm
Column K-2	40 cm	90 cm
Column K-3	40 cm	200 cm
Column K-4	40 cm	150 cm
Column K-5	40 cm	180 cm
Column K-6	35 cm	85 cm

Since column K-7 is a circular column its dimension can not be defined by width and height so it can be defined by its radius dimension where in this case it has a radius of 25 cm.As for the elevator it will be explained according to the upcoming figure.

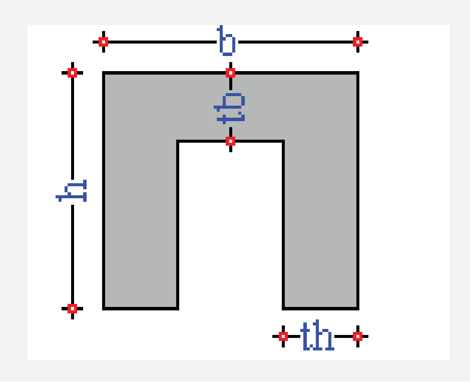


Figure 30. Elevator wall dimensions

According to the figure,tb and th have the same value which in this case has a dimension of 25 cm.The length of the elevator wall which has the b dimension according to the picture,is 400 cm and the width of it has a dimension of 240 cm.After we are done with the columns dimensions let’s check the beams dimensions and positioning.

Figure 31. Beam positioning

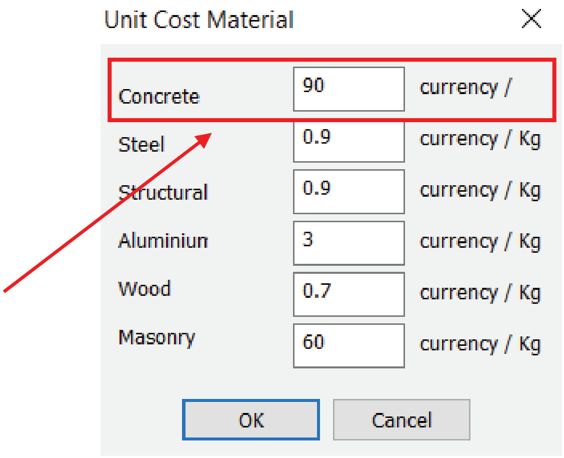
In difference from the columns we don’t have the same variety in beams dimensions.Ther are only two types of beams where the following table will show their dimensions.

Table 2. Dimension of beams

Beam Name	**Width dimension**	**Height dimension**
Beam T-1	80 cm	30 cm
Beam T-2	35 cm	50 cm

4.2 Simulations

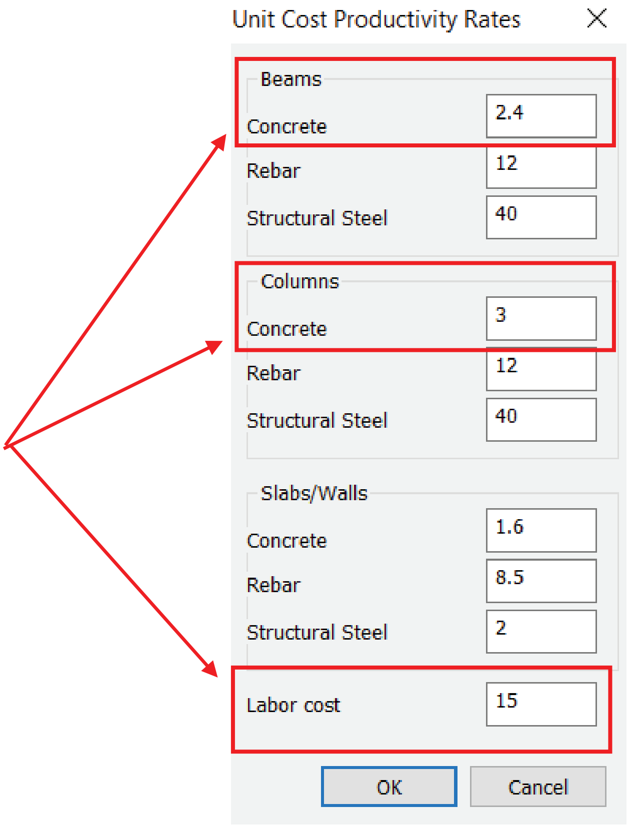
After the 3D model is finished and checked it is ready to go through the optimization process through ACE-OCP.So first we start by putting the values for unit cost materials and unit cost productivity.



Concrete 90 currency /
Steel 0.9 currency / Kg
Structural 0.9 currency / Kg
Aluminiun 3 currency / Kg
Wood 0.7 currency / Kg
Masonry 60 currency / Kg

Figure 32. Unit cost material values

Since we are dealing with a reinforced concrete structures and the optimization will occur only on the concrete density and volume we will be focused on concrete price.The cost of concrete is valued at 120 €/m3 nowadays.



Beams
Concrete 2.4
Rebar 12
Structural Steel 40

Columns
Concrete 3
Rebar 12
Structural Steel 40

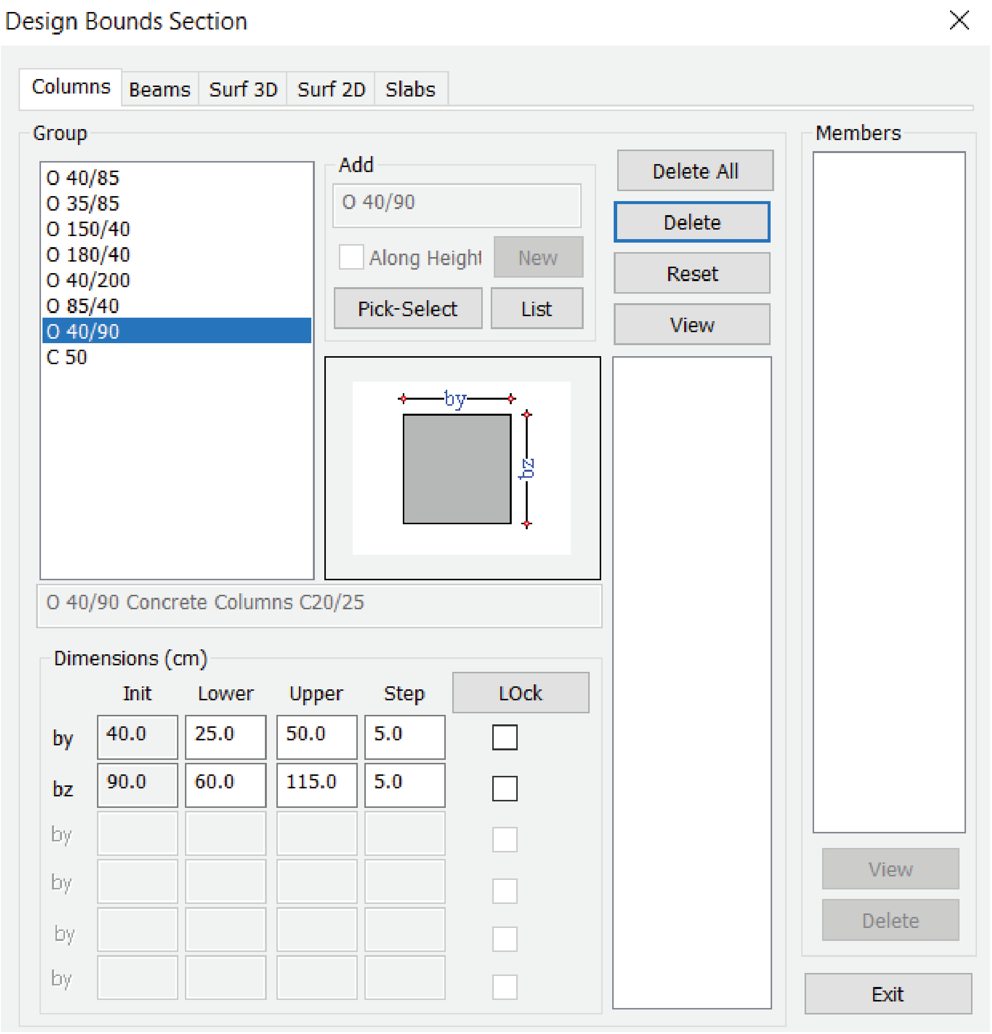
Slabs/Walls
Concrete 1.6
Rebar 8.5
Structural Steel 2

Labor cost 15

Figure 33. Unit cost productivity rates values

The same logic is applied also for the unit cost productivity rates except that in this case we have also to take into account the labor cost.After all this is done the structure is ready for optimization.The cost productivity rate show the hours that are needed to make 1 meter cube of concrete for a column and beam where we can see there are different rates for these members specifically.

The next step is to set the dimension boundaries that we want to put into the optimization process as shown in the following figure.



O 40/85
O 35/85
O 150/40
O 180/40
O 40/200
O 85/40
O 40/90
C 50

O 40/90

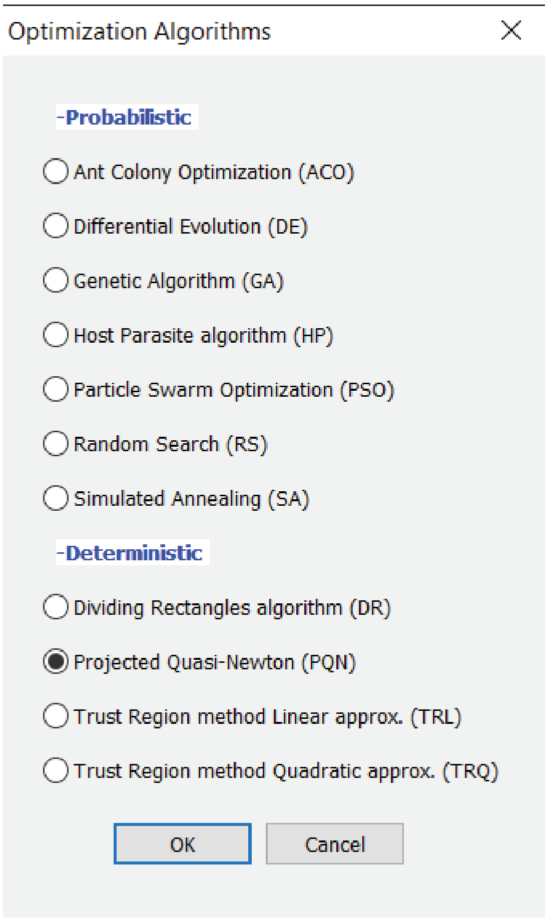
O 40/90 Concrete Columns C20/25

Dimensions (cm)

	Init	Lower	Upper	Step	LOck
by	40.0	25.0	50.0	5.0	☐
bz	90.0	60.0	115.0	5.0	☐
by					☐
by					☐
by					☐
by					☐

Figure 34. Design Bounds Section

This table shows the design boundaries of the columns that we want to set to the structure.In the group window all the columns are included except the elevator wall which means that it will not be set to be optimized during the process because its dimension are fixed and can not be changed due to the elevator size.Below that window we can see the upper and lower boundaries that we want to set to a specific column.At the specific case a column with a width of 40 cm has been set the lower boundary at 25 cm and upper boundaries at 50 cm.It is good to go as much as to the extremes under some logic sense for having more variety in the optimization process.



-Probabilistic

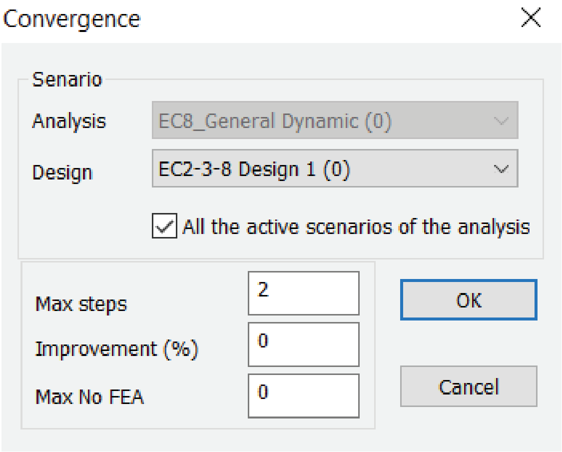
○ Ant Colony Optimization (ACO)
○ Differential Evolution (DE)
○ Genetic Algorithm (GA)
○ Host Parasite algorithm (HP)
○ Particle Swarm Optimization (PSO)
○ Random Search (RS)
○ Simulated Annealing (SA)

-Deterministic

○ Dividing Rectangles algorithm (DR)
● Projected Quasi-Newton (PQN)
○ Trust Region method Linear approx. (TRL)
○ Trust Region method Quadratic approx. (TRQ)

Figure 35. Optimization algorithms

After the design bounds and constraints are set such as the column and beam dimensions the optimization algorithm is chosen and this specific case the PQN technique is chosen.



Senario
Analysis: EC8_General Dynamic (0)
Design: EC2-3-8 Design 1 (0)
☑ All the active scenarios of the analysis

Max steps: 2
Improvement (%): 0
Max No FEA: 0

Figure 36. Improvement percentage

One last step before running the optimization is setting the minimum improvement we want to achieve from this study and in this case 0% is set as shown in the table of convergence.This means that every improvement will be set as an output.For example if it is set 5%,improvements under 5% will not be shown as optimizations outputs.

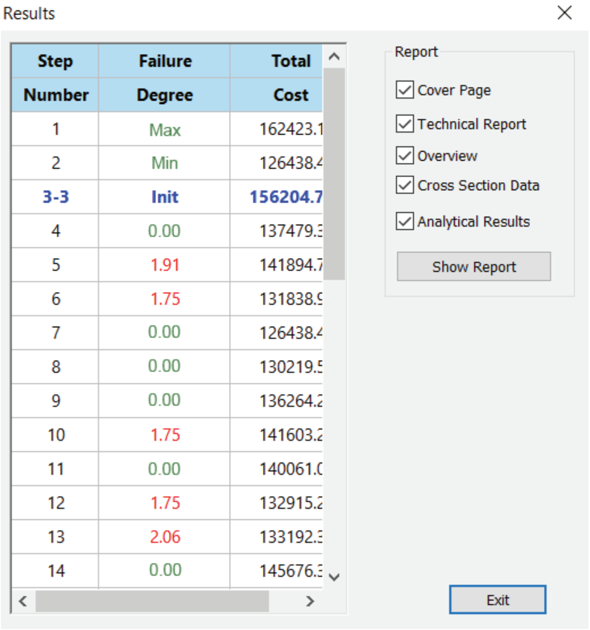
CHAPTER 5

RESULTS AND DISCUSSIONS

After the optimization process is finished a graph is provided for the iterations that have been taken.

Figure 37. Optimization graph results

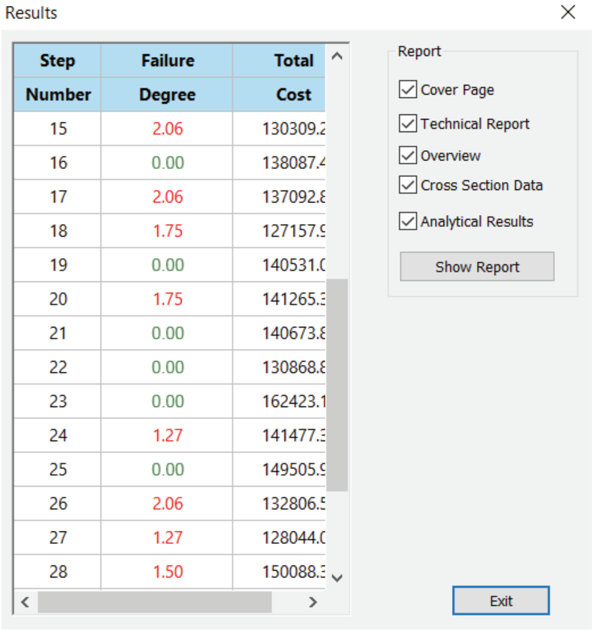
This graph shows the number of the iterations (x axis) that the software has provided and the improvements in % that have been made for each scenario(y axis).



Step Number	Failure Degree	Total Cost
1	Max	162423.1
2	Min	126438.4
3-3	**Init**	**156204.7**
4	0.00	137479.3
5	1.91	141894.7
6	1.75	131838.9
7	0.00	126438.4
8	0.00	130219.5
9	0.00	136264.2
10	1.75	141603.2
11	0.00	140061.0
12	1.75	132915.2
13	2.06	133192.3
14	0.00	145676.3

☑ Cover Page
☑ Technical Report
☑ Overview
☑ Cross Section Data
☑ Analytical Results

Figure 38. Optimization results 1



Step Number	Failure Degree	Total Cost
15	2.06	130309.2
16	0.00	138087.4
17	2.06	137092.8
18	1.75	127157.9
19	0.00	140531.0
20	1.75	141265.3
21	0.00	140673.8
22	0.00	130868.8
23	0.00	162423.1
24	1.27	141477.3
25	0.00	149505.9
26	2.06	132806.5
27	1.27	128044.0
28	1.50	150088.3

Report
- ☑ Cover Page
- ☑ Technical Report
- ☑ Overview
- ☑ Cross Section Data
- ☑ Analytical Results

Figure 39. Optimization results 2

From the graph and from the figures 37,38 and 39 it is concluded that 33 scenarios have been created and the best scenario with the most improvement has achieved to save 19.6% of the cost.As we can see from the tables and the graph some of the results have failure degree which means that the design is not feasible according to EC-8.This brings that those optimized designs are not stable so even if there is saved material it can not be used.For that reason in the graph those improvement are not considered so the study will focus on explaining only those designs that have fulfilled the rules of EC-8.Optimization tool also provides information for the improvement that happens specifically to the concrete for beams and columns respectively as are shown in the following table for each scenario.Every optimized design will be analyzed respectively for every itineration.Itineration

The first itineration as shown in the table results is the maximal cost design which directly means the simulation with less cost decreased.The optimization tool provides the information for the whole concrete volume of the structure and every design member that has changed during the process.The following tables information will explain in more detail.

Table 3. Optimized results on concrete volume simulation nr.1

	Bill of Material	**Concrete (m3)**
Beams	Initial	252.25
	Optimized	265.29
	Improvement(%)	**-3.9%**
Columns	Initial	279.65
	Optimized	291.67
	Improvement(%)	**-4.3%**

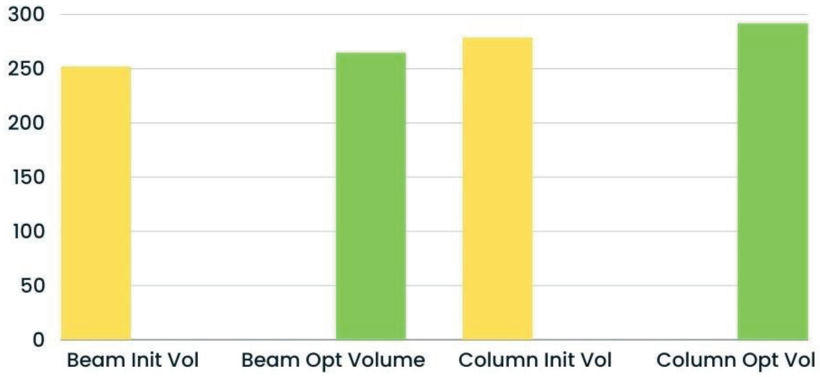


Figure 40. Chart on the optimized volume of columns and beams for simulation nr.1

This chart shows graphically the change in volume from the existing structure to the optimized structure.As we can see for both,columns and beams the optimized volume is higher which means the cost will be higher for this case and the improvement will be negative.

In the following tables the optimized dimension of the columns and beams will be shown in specific for a better understanding of the structure and and how these member affect the new structure.

Table 4. Optimized results on columns for simulation nr.1

Column	**Initial width**	**Optimized width**	**Initial height**	**Optimized height**
Column K-1	40 cm	**45 cm**	85 cm	**85 cm**
Column K-2	40 cm	**45 cm**	90 cm	**80 cm**
Column K-3	40 cm	**45 cm**	200 cm	**155 cm**
Column K-4	40 cm	**50 cm**	150 cm	**135 cm**
Column K-5	40 cm	**35 cm**	180 cm	**185 cm**
Column K-6	35 cm	**25 cm**	85 cm	**65 cm**
Column K-7	r-25 cm	**r-25 cm**	r-25 cm	**r-25 cm**

Table 5. Optimized results on beams for simulation nr.1

Beam	**Initial width**	**Optimized width**	**Initial height**	**Optimized height**
Beam T-1	80 cm	**95 cm**	30 cm	**30 cm**
Beam T-2	35 cm	**45 cm**	50 cm	**35 cm**

As we can see the dimensions of columns have almost all changed in this simulation except the circular shape column which has remanined the same.In most of the columns the width dimension has gotten larger and the longitudinal length has gotten smaller.As for the beams,the depth of beam T-1 has not changed which means it has still remained flat beam which is good for the architecture but on the other side the longitudinal length has gotten more larger which will affect the cost.For the architecture this optimized sample is not the best design because the less the width of the columns the better it would be but in this case the width has gotten larger.Beside that,from the table of optimized concrete volume and the figure of optimization results the structure is heavier and cost is higher than the existing structure.

The second itineration as shown in the table results is the minimal cost design which directly means the simulation with highest cost decreased with a percentage of .The optimization tool provides the information for the whole concrete volume of the structure and every design member that has changed during the process.The following tables information will explain in more detail.

Table 6. Optimized results on concrete volume for simulation nr.2

	Bill of Material	**Concrete (m3)**
	Initial	252.25
Beams	Optimized	189.18
	Improvement(%)	**25%**
	Initial	279.65
Columns	Optimized	237.70
	Improvement(%)	**15%**

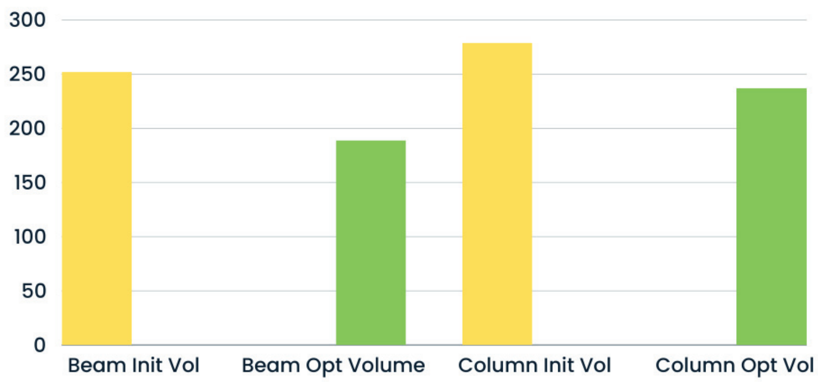


Figure 41. Chart on the optimized volume of columns and beams for simulation nr.2

This chart shows graphically the change in volume from the existing structure to the optimized structure.As we can see for both,columns and beams the optimized volume is lower which means the cost will be less compared to the existing structure for this case and the improvement will be positive.

In the following tables the optimized dimension of the columns and beams will be shown in specific for a better understanding of the structure and and how these member affect the new structure.

Table 7. Optimized results on columns for simulation nr.2

Column	**Initial width**	**Optimized width**	**Initial height**	**Optimized height**
Column K-1	40 cm	**30 cm**	85 cm	**55 cm**
Column K-2	40 cm	**30 cm**	90 cm	**60 cm**
Column K-3	40 cm	**30 cm**	200 cm	**140 cm**
Column K-4	40 cm	**35 cm**	150 cm	**105 cm**
Column K-5	40 cm	**30 cm**	180 cm	**135 cm**
Column K-6	35 cm	**30 cm**	85 cm	**55 cm**
Column K-7	r-25 cm	**r-20 cm**	r-25 cm	**r-20 cm**

Table 8. Optimized results on beams for simulation nr.2

Beam	Initial width	Optimized width	Initial height	Optimized height
Beam T-1	80 cm	**60 cm**	30 cm	**30 cm**
Beam T-2	35 cm	**30 cm**	50 cm	**30 cm**

As we can see the dimensions of all columns have changed in this simulation. In most of the columns the width dimension has gotten smaller and the longitudinal length has gotten smaller too.As for the beams,the depth of beam T-1 has not changed which means it has still remained flat beam which is good for the architecture.As for the longitudinal length,it has also been decreased which means the total volume of the beams will decrease.This optimized sample is a very good proposition design because the less the dimensions of the columns and beams the better it would be for the architecture which will affect the space less than the initial design.Beside that,from the table of optimized concrete volume and the figure of optimization results the structure is lighter in concrete volume and cost is decreased from the existing structure.As a conclusion this sample would be a good result as an optimization result.

The third itineration as shown in the table results is the initial cost design which means the simulation has not changed the structure so the study will move on with the next itineration,which would be itineration number 4 with an optimized cost of 137479 euros.This would bring a 12% decrease of cost from the initial structure which is estimated at 156204 euros.The following tables information will explain in more detail about this itineration.

Table 9. Optimized results on concrete volume for simulation nr.3

	Bill of Material	Concrete (m3)
	Initial	252.25
Beams	Optimized	219.45

	Improvement(%)	**13.1%**
	Initial	279.65
Columns	Optimized	246.09
	Improvement(%)	**12.6%**

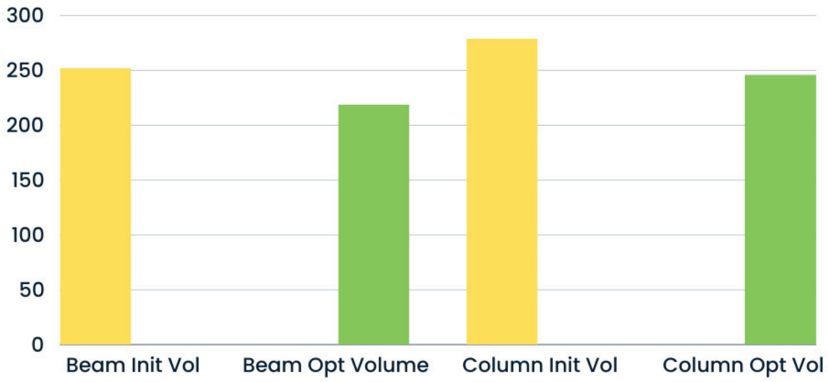


Figure 42. Chart on the optimized volume of columns and beams for simulation nr.3

This chart shows graphically the change in volume from the existing structure to the optimized structure.As we can see for both,columns and beams the optimized volume is lower which means the cost will be less compared to the existing structure for this case and the improvement will be positive.The imptovement for the beams would be 13.1% and for the columns would be 12.6%.

In the following tables the optimized dimension of the columns and beams will be shown in specific for a better understanding of the structure and and how these member affect the new structure.

Table 10. Optimized results on columns for simulation nr.3

Column	**Initial width**	**Optimized width**	**Initial height**	**Optimized height**

Column K-1	40 cm	**35 cm**	85 cm	**55 cm**
Column K-2	40 cm	**45 cm**	90 cm	**100 cm**
Column K-3	40 cm	**40 cm**	200 cm	**170 cm**
Column K-4	40 cm	**30 cm**	150 cm	**125 cm**
Column K-5	40 cm	**40 cm**	180 cm	**215 cm**
Column K-6	35 cm	**30 cm**	85 cm	**75 cm**
Column K-7	r-25 cm	**r-17.5 cm**	r-25 cm	**r-17.5 cm**

Table 11. Optimized results on beams for simulation nr.3

Beam	**Initial width**	**Optimized width**	**Initial height**	**Optimized height**
Beam T-1	80 cm	**70 cm**	30 cm	**30 cm**
Beam T-2	35 cm	**30 cm**	50 cm	**40 cm**

As we can see the dimensions of columns have changed in a better way in this simulation. In most of the columns the width dimension has mostly remained the same but what is different from the previous simulations longitudinal length has gotten smaller and the circular column size has been decreased too.As for the beams in difference from the columns we don’t see the same size changes,meaning the dimensions move with 10 cm up or down.This optimized sample is a good proposition design because the dimension are not changing too much architecturaly but there is a good cost decrease by 12.6% .Beside that,from the table of optimized concrete volume and the figure of optimization results the structure is lighter in concrete volume and cost is decreased from the existing structure.As a conclusion this sample would be a good result as an optimization result.

Itineration number 5 and 6 as we can see from the optimization results table are not feasible results as explained above so it is not necessary to analyze if they are not stable structures.Itineration number 7 is the itineration with the maximal results and savings which is already explained as itineration number 2 so the study will move on with itineration number 8.This itineration has achieved an optimized cost of 130219 euros which would bring a cost decrease by 16.7% from the initial cost. The following tables information will explain in more detail.

Table 12. Optimized results on concrete volume for simulation nr.8

	Bill of Material	**Concrete (m3)**
Beams	Initial	252.25
	Optimized	201.16
	Improvement(%)	**20%**
Columns	Initial	279.65
	Optimized	246.43
	Improvement(%)	**12%**

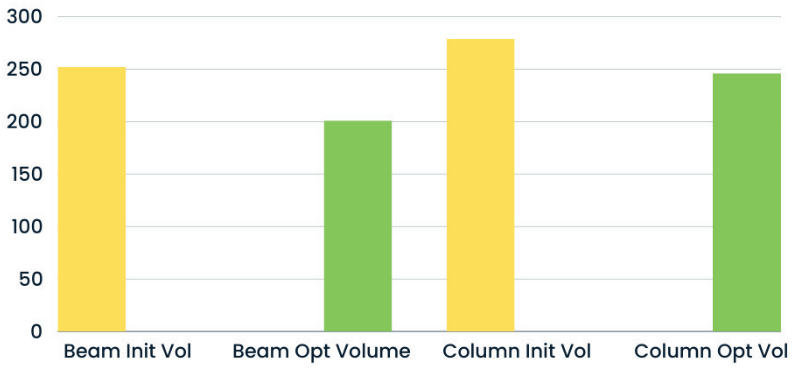


***Figure 43*.** Chart on the optimized volume of columns and beams for simulation nr.8

This chart shows graphically the change in volume from the existing structure to the optimized structure.As we can see for both,columns and beams the optimized volume is lower which means the cost will be less compared to the existing structure for this case and the improvement will be positive.More specifically there would be an improvement of 20% in beams volume and 12% in columns volume.

In the following tables the optimized dimension of the columns and beams will be shown in specific for a better understanding of the structure and and how these member affect the new structure.

***Table 13*.** Optimized results on columns for simulation nr.8

Column	**Initial width**	**Optimized width**	**Initial height**	**Optimized height**
Column K-1	40 cm	**30 cm**	85 cm	**100 cm**
Column K-2	40 cm	**40 cm**	90 cm	**90 cm**
Column K-3	40 cm	**30 cm**	200 cm	**140 cm**
Column K-4	40 cm	**45 cm**	150 cm	**125 cm**
Column K-5	40 cm	**35 cm**	180 cm	**140 cm**
Column K-6	35 cm	**35 cm**	85 cm	**95 cm**
Column K-7	r-25 cm	**r-22.5 cm**	r-25 cm	**r-22.5 cm**

***Table 14*.** Optimized results on beams for simulation nr.8

Beam	**Initial width**	**Optimized width**	**Initial height**	**Optimized height**
Beam T-1	80 cm	**70 cm**	30 cm	**35 cm**

Beam T-2	35 cm	**35 cm**	50 cm	**40 cm**

As we can see the dimensions of all columns width vary between 30 to 45 and the heights of columns have all been decreased except column K-1.As for the beams,the depth of beam T-1 has been increased which means it is not good for the architecture and the cost.As for the longitudinal length,it has also been decreased which means the total volume of the beams will decrease.This optimized sample is a good proposition for cost achievement because 16.7% is not a bad percentage.Beside that,from the table of optimized concrete volume and the figure of optimization results the structure is lighter in concrete volume and cost is decreased from the existing structure.As a conclusion this sample would be a good result as an optimization result.

Itineration number 9 as shown in the table of optimization results is the next one which is feasible and ready to go through analysis.This simulation has achieved an optimized cost of 136264 euros,bringing a cost decrease by 12.8% from the initial cost.The optimization tool provides the information for the whole concrete volume of the structure and every design member that has changed during the process.The following tables information will explain in more detail.

Table 15. Optimized results on concrete volume for simulation nr.9

	Bill of Material	**Concrete (m3)**
	Initial	252.25
Beams	Optimized	234.59
	Improvement(%)	**7%**
	Initial	279.65
Columns	Optimized	229.31

Improvement(%)	**18%**

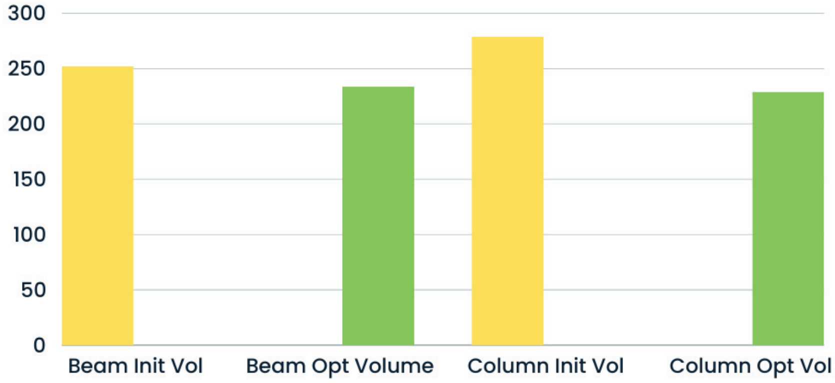


Figure 44. Chart on the optimized volume of columns and beams for simulation nr.9

This chart shows graphically the change in volume from the existing structure to the optimized structure.As we can see for both,columns and beams the optimized volume is lower which means the cost will be less compared to the existing structure for this case and the improvement will be positive.More specifically there will be an improvement of 7% for the beams and 18% for the columns.

In the following tables the optimized dimension of the columns and beams will be shown in specific for a better understanding of the structure and and how these member affect the new structure.

Table 16. Optimized results on columns for simulation nr.9

Column	**Initial width**	**Optimized width**	**Initial height**	**Optimized height**
Column K-1	40 cm	**30 cm**	85 cm	**65 cm**
Column K-2	40 cm	**45 cm**	90 cm	**60 cm**
Column K-3	40 cm	**30 cm**	200 cm	**155 cm**

Column K-4	40 cm	**35 cm**	150 cm	**145 cm**
Column K-5	40 cm	**45 cm**	180 cm	**200 cm**
Column K-6	35 cm	**35 cm**	85 cm	**85 cm**
Column K-7	r-25 cm	**r-20 cm**	r-25 cm	**r-20 cm**

Table 17. Optimized results on beams for simulation nr.9

Beam	**Initial width**	**Optimized width**	**Initial height**	**Optimized height**
Beam T-1	80 cm	**80 cm**	30 cm	**30 cm**
Beam T-2	35 cm	**30 cm**	50 cm	**35 cm**

In this itineration a good improvement has happened to the columns.As for the beams, beam T-1which contains the most of the volume which bring a light improvement to the structure.Eventhough it is not saved too much in beams it is compensated from the columns which have achieved a good optimization result. Beside that,from the table of optimized concrete volume and the figure of optimization results the structure is lighter in concrete volume and cost is decreased from the existing structure.As a conclusion this sample would be a good result as an optimization result.

Itineration number 10 as we can see from the optimization results table is also not feasible as explained above so it is not necessary to analyze because it is not a stable structure.This means the next itineration that will be explained is itineratioin number 11.Through the optimization the new structure cost was decreased by 10.4% from the initial design. The following tables information will explain in more detail.

Table 18. Optimized results on concrete volume for simulation nr.11

	Bill of Material	**Concrete (m3)**
	Initial	252.25
Beams	Optimized	231.56
	Improvement(%)	**8.2%**
	Initial	279.65
Columns	Optimized	240.49
	Improvement(%)	**13.4%**

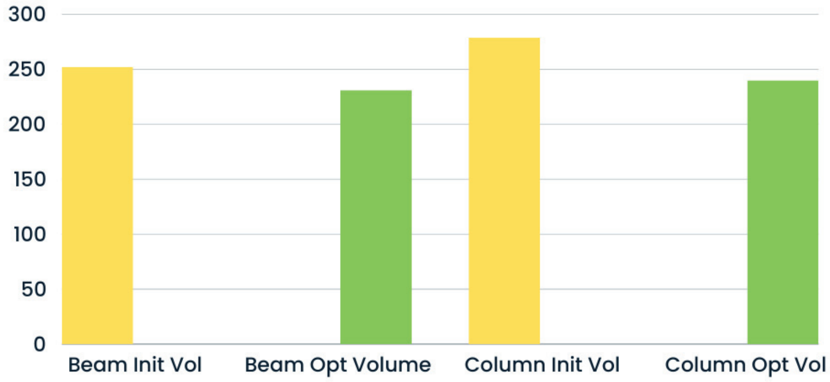


Figure 45. Chart on the optimized volume of columns and beams for simulation nr.11

This chart shows graphically the change in volume from the existing structure to the optimized structure.As we can see for both,columns and beams the optimized volume is lower which means the cost will be less compared to the existing structure for this case and the improvement will be positive.More specifically there will be an improvement of 8.2% for the beams and 13.4% for the columns.

In the following tables the optimized dimension of the columns and beams will be shown in specific for a better understanding of the structure and and how these member affect the new structure.

Table 19. Optimized results on columns for simulation nr.11

Column	**Initial width**	**Optimized width**	**Initial height**	**Optimized height**
Column K-1	40 cm	**30 cm**	85 cm	**85 cm**
Column K-2	40 cm	**35 cm**	90 cm	**60 cm**
Column K-3	40 cm	**30 cm**	200 cm	**140 cm**
Column K-4	40 cm	**45 cm**	150 cm	**115 cm**
Column K-5	40 cm	**45 cm**	180 cm	**125 cm**
Column K-6	35 cm	**45 cm**	85 cm	**85 cm**
Column K-7	r-25 cm	**r-27.5 cm**	r-25 cm	**r-27.5 cm**

Table 20. Optimized results on beams for simulation nr.11

Beam	**Initial width**	**Optimized width**	**Initial height**	**Optimized height**
Beam T-1	80 cm	**65 cm**	30 cm	**30 cm**
Beam T-2	35 cm	**30 cm**	50 cm	**50 cm**

In difference from other simulations in this one there has not happened a big change in the column K-1 but it is compensated from the rest of other columns where the longitudinal length of each has decreased a lot.As for the beams, T-1 has changed its width by lowering 15 cm which has affected in fact almost all the optimized model positively .This optimized sample is a good proposition design with a cost of 10.1% reduced.Beside that,from the table of optimized concrete volume and the figure of optimization results the structure is lighter in concrete volume and cost is decreased from the existing structure.As a conclusion this sample would be a good result as an optimization result.

Itineration number 12 and 13 as we can see from the optimization results table are also not feasible as explained above so it is not necessary to analyze because it is not a stable structure.This means the next itineration that will be explained is itineration number 14 with an optimized cost of 145676 euros,reducing the total cost by 6.8% compared to the initial structure. The following tables information will explain in more detail.

Table 21. Optimized results on concrete volume for simulation nr.14

	Bill of Material	**Concrete (m3)**
	Initial	252.25
Beams	Optimized	256.27
	Improvement(%)	**-1.2%**
	Initial	279.65
Columns	Optimized	252.52
	Improvement(%)	**9.7%**

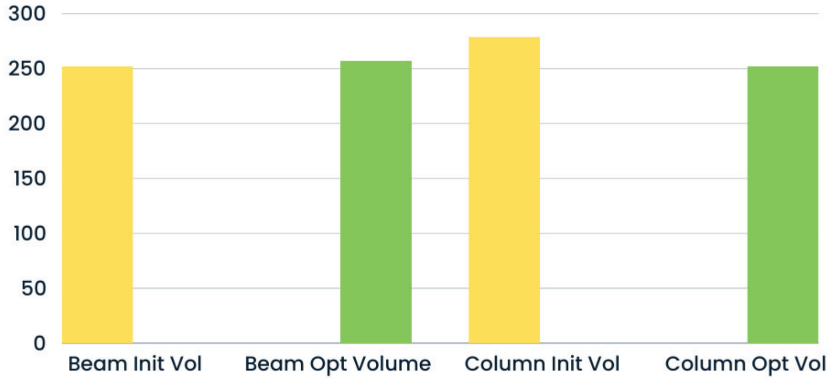


Figure 46. Chart on the optimized volume of columns and beams for simulation nr.14

This chart shows graphically the change in volume from the existing structure to the optimized structure.As we can see in this case different from the other ones the graph shows an increase of volume for beams but a decrease of volume for columns.More specifically regarding to table 21 there is a negative improvement for beams by -1.2% and a positive improvement by 9,7% for the columns which in overall,would make the optimized structure still less expensive.

In the following tables the optimized dimension of the columns and beams will be shown in specific for a better understanding of the structure and and how these member affect the new structure.

Table 22. Optimized results on columns for simulation nr.14

Column	**Initial width**	**Optimized width**	**Initial height**	**Optimized height**
Column K-1	40 cm	**40 cm**	85 cm	**55 cm**
Column K-2	40 cm	**40 cm**	90 cm	**70 cm**
Column K-3	40 cm	**40 cm**	200 cm	**170 cm**
Column K-4	40 cm	**35 cm**	150 cm	**135 cm**
Column K-5	40 cm	**45 cm**	180 cm	**125 cm**

Column K-6	35 cm	**30 cm**	85 cm	**65 cm**
Column K-7	r-25 cm	**r-30 cm**	r-25 cm	**r-30cm**

Table 23. Optimized results on beams for simulation nr.1

Beam	**Initial width**	**Optimized width**	**Initial height**	**Optimized height**
Beam T-1	80 cm	**80 cm**	30 cm	**30 cm**
Beam T-2	35 cm	**30 cm**	50 cm	**60 cm**

As for the columns this scenario looks similar to a previous one above where the width of columns would not change too much but what makes the optimization effective is the length of each where almost all have decreased a lot..As for the beams there is a light negative result because the T-1 beam has not changed and there is an increase in the length of beam T-2.Eventhough there is loss in beams this optimized sample is still a positive proposition design by reducing the total cost of the structure by 6.8%.Beside that,from the table of optimized concrete volume and the figure of optimization results the structure is lighter in concrete volume and cost is decreased from the existing structure.

Itineration number 15 as we can see from the optimization results table is also not feasible as explained above so it is not necessary to analyze because it is not a stable structure.This means the next itineration that will be explained is itineratioin number 16 with an optimized cost of 138087 euros which means there is a 11,2% decrease of cost compared to the initial cost which is 156204 euros. The following tables information will explain in more detail.

Table 24. Optimized results on concrete volume for simulation nr.16

	Bill of Material	**Concrete (m3)**
Beams	Initial	252.25
	Optimized	235.34
	Improvement(%)	**6.7%**
Columns	Initial	279.65
	Optimized	242.17
	Improvement(%)	**13.4%**

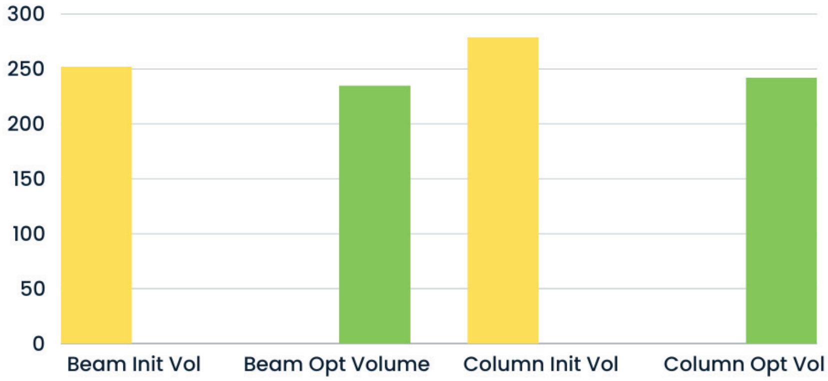


Figure 47. Chart on the optimized volume of columns and beams for simulation nr.16

This chart shows graphically the change in volume from the existing structure to the optimized structure.As we can see for both,columns and beams the optimized volume is lower which means the cost will be less compared to the existing structure for this case and the improvement will be positive.

In the following tables the optimized dimension of the columns and beams will be shown in specific for a better understanding of the structure and and how these member affect the new structure.

Table 25. Optimized results on columns for simulation nr.16

Column	**Initial width**	**Optimized width**	**Initial height**	**Optimized height**
Column K-1	40 cm	**35 cm**	85 cm	**65 cm**
Column K-2	40 cm	**40 cm**	90 cm	**80 cm**
Column K-3	40 cm	**30 cm**	200 cm	**205 cm**
Column K-4	40 cm	**40 cm**	150 cm	**150 cm**
Column K-5	40 cm	**30 cm**	180 cm	**170 cm**
Column K-6	35 cm	**35 cm**	85 cm	**85 cm**
Column K-7	r-25 cm	**r-27.5 cm**	r-25 cm	**r-27.5cm**

Table 26. Optimized results on beams for simulation nr.16

Beam	**Initial width**	**Optimized width**	**Initial height**	**Optimized height**
Beam T-1	80 cm	**70 cm**	30 cm	**30 cm**
Beam T-2	35 cm	**35 cm**	50 cm	**50 cm**

As we can see the dimensions of all columns have changed in this simulation. In most of the columns the width dimension has gotten smaller and the longitudinal length has gotten smaller too.As for the beams,the depth of beam T-1 has not changed which means it has still remained flat beam which is good for the architecture.As for the longitudinal length,it has also been decreased which means the total volume of the beams will decrease.This optimized sample is a very good proposition design because the less the dimensions of the columns and beams the better it would be for the architecture which will affect the space less than the initial design.Beside that,from the table of optimized concrete volume and the figure of optimization results the structure is lighter in concrete volume and cost is decreased from the existing structure.As a conclusion this sample would be a good result as an optimization result.

Itineration number 17 and 18 as we can see from the optimization results table are also not feasible as explained above so it is not necessary to analyze because it is not a stable structure.This means the next itineration that will be explained is itineratioin number 19 with an optimized cost of 140531 euros which means there is a 10.1 % decrease of cost compared to the initial cost which is 156204 euros. The following tables information will explain in more detail.

Table 27. Optimized results on concrete volume for simulation nr.19

	Bill of Material	**Concrete (m3)**
	Initial	252.25
Beams	Optimized	231.31
	Improvement(%)	**8.3%**
	Initial	279.65
Columns	Optimized	247.21
	Improvement(%)	**11.6%**

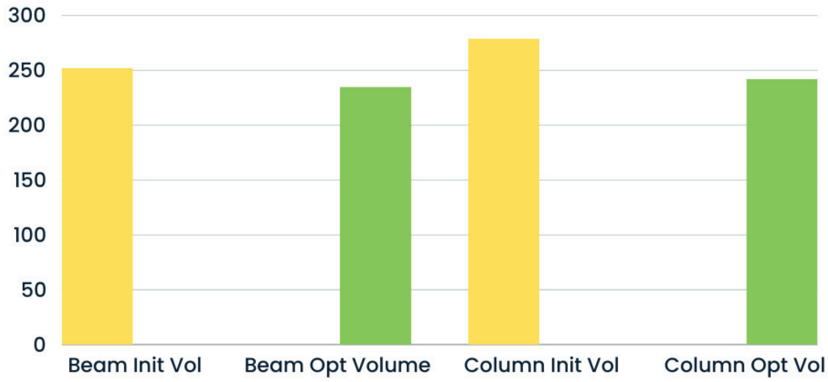


Figure 48. Chart on the optimized volume of columns and beams for simulation nr.19

This chart shows graphically the change in volume from the existing structure to the optimized structure.As we can see for both,columns and beams the optimized volume is lower which means the cost will be less compared to the existing structure for this case and the improvement will be positive.

In the following tables the optimized dimension of the columns and beams will be shown in specific for a better understanding of the structure and and how these member affect the new structure.

Table 28. Optimized results on columns for simulation nr.19

Column	**Initial width**	**Optimized width**	**Initial height**	**Optimized height**
Column K-1	40 cm	**45 cm**	85 cm	**55 cm**
Column K-2	40 cm	**45 cm**	90 cm	**100 cm**
Column K-3	40 cm	**30 cm**	200 cm	**200 cm**
Column K-4	40 cm	**35 cm**	150 cm	**155 cm**
Column K-5	40 cm	**45 cm**	180 cm	**175 cm**
Column K-6	35 cm	**35 cm**	85 cm	**85 cm**
Column K-7	r-25 cm	**r-25 cm**	r-25 cm	**r-25 cm**

Table 29. Optimized results on beams for simulation nr.19

Beam	Initial width	Optimized width	Initial height	Optimized height
Beam T-1	80 cm	**90 cm**	30 cm	**30 cm**
Beam T-2	35 cm	**35 cm**	50 cm	**40 cm**

As we can see the dimensions of all columns have changed in this simulation. In most of the columns the width dimension has gotten smaller and the longitudinal length has gotten smaller too.As for the beams,the depth of beam T-1 has not changed which means it has still remained flat beam which is good for the architecture.As for the longitudinal length,it has also been decreased which means the total volume of the beams will decrease.This optimized sample is a very good proposition design because the less the dimensions of the columns and beams the better it would be for the architecture which will affect the space less than the initial design.Beside that,from the table of optimized concrete volume and the figure of optimization results the structure is lighter in concrete volume and cost is decreased from the existing structure.As a conclusion this sample would be a good result as an optimization result.

Itineration number 20 as we can see from the optimization results table is also not feasible as explained above so it is not necessary to analyze because it is not a stable structure.This means the next itineration that will be explained is itineratioin number 21 with an optimized cost of 140673 euros which means there is a 10% decrease of cost compared to the initial cost which is 156204 euros. The following tables information will explain in more detail.

Table 30. Optimized results on concrete volume for simulation nr.21

	Bill of Material	Concrete (m3)
	Initial	252.25
Beams	Optimized	221.47

	Improvement(%)	**12.1%**
	Initial	279.65
Columns	Optimized	253.36
	Improvement(%)	**9.4%**

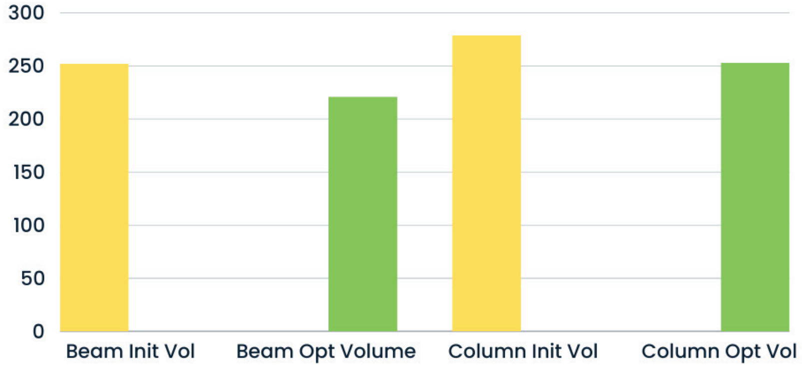


Figure 49. Chart on the optimized volume of columns and beams for simulation nr.21

This chart shows graphically the change in volume from the existing structure to the optimized structure.As we can see for both,columns and beams the optimized volume is lower which means the cost will be less compared to the existing structure for this case and the improvement will be positive.More specifically there would be an improvement of 12.1% for beams and 9.4% for the columns.

In the following tables the optimized dimension of the columns and beams will be shown in specific for a better understanding of the structure and and how these member affect the new structure.

Table 31. Optimized results on columns for simulation nr.21

Column	**Initial width**	**Optimized width**	**Initial height**	**Optimized height**

Column K-1	40 cm	**35 cm**	85 cm	**65 cm**
Column K-2	40 cm	**45 cm**	90 cm	**70 cm**
Column K-3	40 cm	**40 cm**	200 cm	**155 cm**
Column K-4	40 cm	**35 cm**	150 cm	**135 cm**
Column K-5	40 cm	**40 cm**	180 cm	**170 cm**
Column K-6	35 cm	**40 cm**	85 cm	**85 cm**
Column K-7	r-25 cm	**r-25 cm**	r-25 cm	**r-25 cm**

Table 32. Optimized results on beams for simulation nr.21

Beam	**Initial width**	**Optimized width**	**Initial height**	**Optimized height**
Beam T-1	80 cm	**60 cm**	30 cm	**30 cm**
Beam T-2	35 cm	**30 cm**	50 cm	**45 cm**

As we can see the dimensions of all columns have changed in this simulation. In most of the columns the width dimension has gotten smaller and the longitudinal length has gotten smaller too.As for the beams,the depth of beam T-1 has not changed which means it has still remained flat beam which is good for the architecture.As for the longitudinal length,it has also been decreased which means the total volume of the beams will decrease.Beside that,from the table of optimized concrete volume and the figure of optimization results the structure is lighter in concrete volume and cost is decreased from the existing structure.As a conclusion this sample would be a good result as an optimization result.

The next itineration that will be explained is itineratioin number 22 with an optimized cost of 130868 euros which means there is a 16.3% decrease of cost compared to the initial cost which is 156204 euros. The following tables information will explain in more detail.

Table 33. Optimized results on concrete volume for simulation nr.22

	Bill of Material	**Concrete (m3)**
Beams	Initial	252.25
	Optimized	215.16
	Improvement(%)	**14.7%**
Columns	Initial	279.65
	Optimized	231.27
	Improvement(%)	**17.3%**

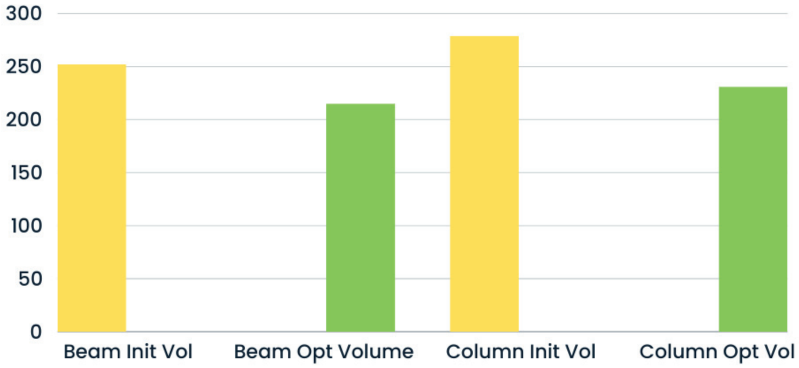


Figure 50. Chart on the optimized volume of columns and beams for simulation nr.22

This chart shows graphically the change in volume from the existing structure to the optimized structure.As we can see for both,columns and beams the optimized volume is lower than most of other simulations which means the cost will be less compared to the other structures and the improvement will be more positive.More specifically that improvement would be 14.7% in beams and 17,3% in columns.

In the following tables the optimized dimension of the columns and beams will be shown in specific for a better understanding of the structure and and how these member affect the new structure.

Table 34. Optimized results on columns for simulation nr.22

Column	**Initial width**	**Optimized width**	**Initial height**	**Optimized height**
Column K-1	40 cm	**35 cm**	85 cm	**80 cm**
Column K-2	40 cm	**35 cm**	90 cm	**70 cm**
Column K-3	40 cm	**25 cm**	200 cm	**230 cm**
Column K-4	40 cm	**35 cm**	150 cm	**165 cm**
Column K-5	40 cm	**30 cm**	180 cm	**155 cm**
Column K-6	35 cm	**35 cm**	85 cm	**85 cm**
Column K-7	r-25 cm	**r-22.5 cm**	r-25 cm	**r-22.5 cm**

Table 35. Optimized results on beams for simulation nr.22

Beam	**Initial width**	**Optimized width**	**Initial height**	**Optimized height**
Beam T-1	80 cm	**70 cm**	30 cm	**30 cm**
Beam T-2	35 cm	**35 cm**	50 cm	**45 cm**

As we can see the dimensions of all columns have changed in this simulation. In most of the columns the width dimension has gotten smaller and the longitudinal length has gotten smaller too.This simulation looks similar to itineration number 2 where the most cost productive result was achieved.As for the beams,the depth of beam T-1 has not changed which means it has still remained flat beam which is good for the architecture.The longitudinal length,it has also been decreased which means the total volume of the beams will decrease.This optimized sample is a very good proposition design because the less the dimensions of the columns and beams the better it would be for the architecture which will affect the space less than the initial design.Beside that,from the table of optimized concrete volume and the figure of optimization results the structure is lighter in concrete volume and cost is decreased from the existing structure.As a conclusion this sample would be a good result as an optimization result.

The next itineration is itineration number 23 but looking at the table of optimization results it is the maximal cost design which is already explained as the first one,so the next one would be itineration number 24 but that design is not a feasible one so that would make itineration number 25 the design that will be explained with an optimized cost of 149505 euros.It means there is a 4.3% decrease of cost compared to the initial cost which is 156204 euros. The following tables information will explain in more detail.

Table 36. Optimized results on concrete volume for simulation nr.25

	Bill of Material	**Concrete (m3)**
Beams	Initial	252.25
	Optimized	243.92
	Improvement(%)	**3.3%**
Columns	Initial	279.65
	Optimized	262.31
	Improvement(%)	**6.2%**

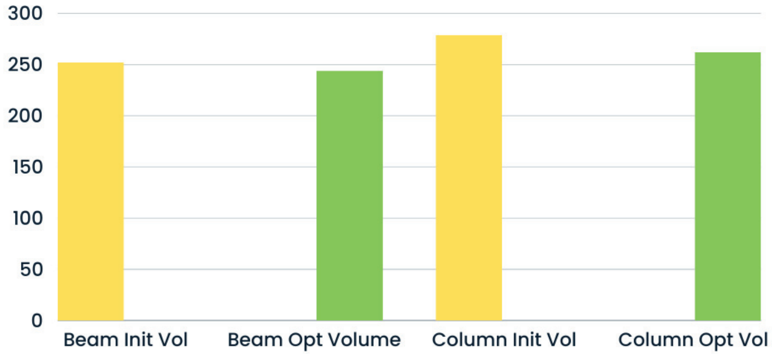


Figure 51. Chart on the optimized volume of columns and beams for simulation nr.25

This chart shows graphically the change in volume from the existing structure to the optimized structure.As we can see for both,columns and beams the optimized volume is lower but in this case for both columns and beams this decrease of volume is not that high which will bring less saving.More specifically there will be a decrease of 3.3% volume for beams and 6.2% for columns.

In the following tables the optimized dimension of the columns and beams will be shown in specific for a better understanding of the structure and and how these member affect the new structure.

Table 37. Optimized results on columns for simulation nr.25

Column	**Initial width**	**Optimized width**	**Initial height**	**Optimized height**
Column K-1	40 cm	**40 cm**	85 cm	**85 cm**
Column K-2	40 cm	**35 cm**	90 cm	**90 cm**
Column K-3	40 cm	**40 cm**	200 cm	**210 cm**
Column K-4	40 cm	**30 cm**	150 cm	**115 cm**
Column K-5	40 cm	**40 cm**	180 cm	**185 cm**

Column K-6	35 cm	**35 cm**	85 cm	**95 cm**
Column K-7	r-25 cm	**r-30 cm**	r-25 cm	**r-30 cm**

Table 38. Optimized results on beams for simulation nr.25

Beam	**Initial width**	**Optimized width**	**Initial height**	**Optimized height**
Beam T-1	80 cm	**75 cm**	30 cm	**30 cm**
Beam T-2	35 cm	**30 cm**	50 cm	**50 cm**

As we can see the dimensions of all columns and beams have not changed a lot compared to the initial members.This makes sense why the improvement is so small in percentage for the overall structure.have changed in this simulation.Beside that,from the table of optimized concrete volume and the figure of optimization results the structure is lighter in concrete volume and cost is decreased from the existing structure.As a conclusion this sample would need a better judgment if it is worthy of taking the time of design for this percentage of savings.

CHAPTER 6

CONCLUSIONS

In this thesis, it was investigated the structural optimizations of reinforced concrete structures in cost efficiency. The question this thesis addresses is the price increase of construction in Albania and how structural optimization can help with the improvement in cost savings.Structural optimization has been a great help in construction for the last decades.It is being improved day by day with the help of computional power and new techniques and methods that are being developed.Something like this is missing Albania and it should be part of construction for the benefit of all including the engineers,owners,clients etc.

The study was focused on a typical building in Tirana which it’s construction is a reinforced concrete structure.Since the slabs are brick slabs,simulations couldn’t be done on them so the only way to apply optimization was through columns and beams.Practically this type of construction is found in almost every building in Tirana and other cities so this study is a good example for other buildings.

The optimization was achieved through SCADA PRO software which has it’s own optimization tool (ACE-OCP).This tool is a very powerful one because it includes different optimization techniques such as probabilistic algorithms and deterministic algorithms.It can be applied in reinforced concrete structures such as columns,beams,shear walls,slabs,foundation and in steel structures.Specifically in this study it was used for concrete structures such as beams and columns because this is the most used type of construction in Albania.It is used Projected Quasi-Newton algorithm which is a part of deterministic algorithms.

After the structure was modelled and optimized very satisfying results were concluded.With many iteration and scenarios it was finalized with the best one which has an improvement of 19.1% in cost efficiency.The initial cost was 156,204 euros and the cost after the simulations went down to 126,438 euros.

Considering that the optimization is done in an reinforced concrete structure similar to Albanian type of construction this is a very good news for the construction world in Albania.It can be the first step in applying structural optimization in the real world civil-engineering and architecture projects.These can be the first steps into civil-engineering and architecture where the cost is precisely the least it can be and removing the old way of construction through trial and error.

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