Civil Engineering Department

Laboratory of Earthquake Engineering and Structural Dynamics

Final Year Project Report Presented in Partial Fulfilment of the Requirements for the Civil Engineering Degree

Automation and Optimization of RC Dual Systems for Earthquake Resisting Buildings Using a Genetic Algorithm in BIM Environment

Presented by:

Saber LARFI

Khelil SOUACI

Supervisors:

M. N. BOURAHLA

M. S. TAFRAOUT

Defended on 07/07/2021

Jury members:

President	M. Abderrahim BALI	Prof.	ENP
Supervisors	M. Nouredine BOURAHLA	Prof.	ENP
	M. Salim Tafraout	Ingénieur.	SCTE
Examiner	Mrs. Sana STIHI	M.A.A.	ENP
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المدرسة الوطنية المتعددة التقنيات
Ecole Nationale Polytechnique

LGSDS

Département de Génie Civil

Laboratoire de Génie Sismique et Dynamique des Structures

Mémoire de fin d'études

pour l'obtention du diplôme d'ingénieur d'état en Génie Civil

Automatisation et Optimisation des Systèmes Dual en BA pour les Bâtiments Résistants aux Séismes à l'aide d'un Algorithme Génétique dans un Environnement BIM

Réalisé par :

LARFI Saber

SOUACI Khelil

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Composition du Jury :

President	M. Abderrahim BALI	Prof.	ENP
Promoteurs	M. Nouredine BOURAHLA	Prof.	ENP
	M. Salim Tafraout	Ingénieur.	SCTE
Examinatrice	Mrs. Sana STIHI	M.A.A.	ENP
Examinateur	M. Mustapha DEMIDEM	M.A.A.	ENP

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ملخص

في خضم ما نشهده اليوم من تطور تكنولوجي مبهر، تعيش العديد من القطاعات الصناعية ازدهارا و تقدما هائلا منذ العقود الماضية، بيد أن أكبر هذه القطاعات و المسماة بقطاع البناء و الانشاءات تبدو أقل تبنيا لما يتوفر اليوم من فرص و معدات قدمتها لنا التكنولوجيا ، السبب الذي جعلها تبدو أقل تطورا. و بالرجوع الى جذور المشاكل نجد أن تنوع الشركاء و المساهمين في عملية البناء كالمهندس المدني و المعماري و غيرهم و صعوبة ايجاد المرونة الكافية للتفاهم فيما بينهم كان سببا مباشرا في هذا التأخر. تعتبر منصات BIM تقنية حديثة تساهم بشكل مباشر في معالجة هذا العيب من خلال تسهيل عمليات نقل و مشاركة المعلومات بين مختلف التخصصات المشاركة في هذا المجال في مراحل متقدمة قبل الخوض في غمار العملية بشكل أعمق. في هذا السياق ، تعتمد هذه الأطروحة في دراستها على خوارزميتين، أولتهما الخوارزمية الجينية GA و ثانيتهما خوارزمية البحث TS بغية الحصول على أحسن و أفضل تصميم هيكلي للمباني ذات الأنظمة المزدوجة، الأنظمة التي تتكون من جدران قص و أعمدة تساهم في جعل هاته البنايات قادرة على مقاومة الزلازل و غيرها . حيث تستعمل الخوارزمية الجينية خصيصا لجدران القص لايجاد أفضل المواقع المحتملة لتثبيتها بالاضافة الى أطوال هاته الأخيرة. أما بالنسبة للأعمدة فهي الأخرى لها أيضا مواقع في المبنى أفضل من أخرياتها و لإيجادها يتم تطبيق الخوارزمية الثانية TS. في الأخير، أثبتت كلتا الخوارزميتين فعاليتهما في انشاء هياكل محسنة وفق عملية تعتمد على تحسين متعدد الأهداف، و هذا ما سمح بمزيد من الحرية للمهندس المعماري و تصاميمه، كما سمح باستكشاف فرص و احتمالات أكثر للهيكلة.

كلمات مفتاحية : جدران القص ، نمذجة معلومات المباني BIM ، الأنظمة الانشائية المزودجة RCDS ، الخوارزمية الجينية GA ، خوارزمية البحث TS.

Résumé

En cette ère de progrès technologiques, la plupart des secteurs de l'industrie ont connu d'énormes progrès au cours des dernières décennies et ont tiré profit des innovations de procédés et de produits. Le secteur de la construction, cependant, reste hésitant à saisir pleinement les dernières opportunités technologiques, ce qui se traduit par un retard d'automatisation du secteur. On constate que la diversité des partenaires et des disciplines impliqués dans le processus (AEC) et la nature itérative de la procédure de conception ont entraîné ce retard vers la tendance de l'automatisation. Le BIM est une technologie émergente qui répond à cet inconvénient en fournissant un espace pour le partage de l'information et en aidant au contrôle interdisciplinaire pendant la phase conceptuelle et les étapes ultérieures. Dans ce contexte, le présent projet adapte à la fois l'algorithme génétique et l'algorithme tabu search (TS) pour automatiser et optimiser la conception structurelle des systèmes Voiles-portiques avec interaction pour les bâtiments résistants aux séismes au sein d'une plateforme BIM. Enfin, un algorithme génétique avec une fonction multi-objectifs est appliqué pour générer une disposition optimisée des voiles sous différents ensembles de contraintes structurelles.

Mots Clés : Béton armé, des voiles et des portiques, BIM, Algorithme génétique, Tabu search.

Abstract

In the current era of technological advancements, most of the industry sectors have undergone tremendous progress over the last few decades and have reaped the benefits of process and product innovations. The Engineering & Construction sector, however, has been hesitant about fully embracing the latest technological opportunities. Back to the problems, it is found that the diversity of the partners and disciplines involved in the architecture, engineering and construction process and the iterative nature of the design procedure caused that delay towards the trend of automation and optimization. The building information modelling (BIM) environment is an emerging technology which address that drawback by providing a space for information sharing and helping the inter-disciplinary check during the conceptual phase and further stages. In this context, the present project adapts both genetic algorithm and tabu search (TS) to automate and optimize the structural design of RC dual systems for earthquake resisting buildings within a BIM platform. Finally, a genetic algorithm with multi-objective function is applied to generate an optimized structural shear walls layout under different set of structural constraints.

Keywords: RCDS, BIM, Structural optimization, Genetic algorithm, Tabu search.

Dedications

I take the chance to express my gratitude and thankfulness to all those who have been by my side throughout this long journey. Thereby, I dedicate this dissertation to

The two whom without their support, inspiration, and drive, I might have not achieved what I have today, my beloved parents.

Those who were available in times of need and difficulties, my brothers, and relatives.

Everyone who shared this path with me, my supportive classmates.

And finally, my only and best friend.

Saber LARFI

I would like to seize this opportunity to express my genuine gratitude and warm appreciation to everyone who never left my side in times of need. Therefore, I dedicate this

modest work

To the captains of my ship, the two who have always been the fuel of my life, and source of inspiration, my beloved parents.

To my relatives, who never ceased ringing my ears with words of encouragement and never refused helping me getting over my hardships.

To my best friends and classmates, special thanks to you.

Finally, a heartfelt regard to the one who taught me how to read and write, my very first teacher, Meriem.

Khelil SOUACI

Acknowledgements

Summary

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List of Abbreviations

RCDS: Reinforced Concrete Dual System

AEC: Architecture Engineering Construction

TS: Tabu Search

GA: Genetic algorithm.

IFC: Industry Foundation Classes

BIM: Building Information Modelling

CAD: Computer aided design

SWP: Shear wall panels

AISI: American Iron and Steel Institute

RPA: Règlement Parasismique Algérien (Algerian Earthquake Resistant Regulations)

CDE: Common Data Environment

EDMS: Electronic Document Management System

MEP: Mechanical, Electrical and Plumbing

ML: Machine Learning

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General Introduction

General introduction

This study has been conducted in the framework of the final year project (PFE) proposed by SCTE (consulting company) and the LGSDS laboratory under the Civil Engineering Department. It presents an innovative approach for automatic design of RC dual system structures, based on the two, genetic and Tabu search algorithms that automatically derive the optimal arrangement of the structural elements for a given architectural configuration in a BIM platform.

Motivation and scope

The construction industry is a fragmented sector which relies on a seamless interplay of numerous partners along the value chain of project's life cycle. There is a need to enhance coordination, cooperation, and information exchange to streamline the whole process of the construction industry. In this context, this study presents an innovative approach related to the process of design to help automatize the interface between disciplines especially architecture and structural engineering which can be easily implemented in a BIM environment. This is a 3D intelligent model-based process that gives architecture, engineering, and construction (AEC) professionals the insight and tools to more efficiently plan, design, construct, and manage buildings and infrastructures.

Objectives

The main objective of this study is to develop a procedure to automatize the structural design of RC dual system buildings, by implementing design rules and criteria required by the Algerian Earthquake Resistant Regulations (RPA) for this type of structures.

The process involves an intelligent approach based on a two stages optimization technique using combined tabu search (TS) algorithm to define a structural grid of columns and a genetic algorithm to generate a shear wall configuration in order to obtain an optimized dual system solution for a given architectural configuration.

Outline of the thesis

This report begins with an overall introduction that portrays the undertaken research work, indicating the inspiration, the scope as well as the adopted approach.

The first chapter hands over general information about the trend of the industrial revolution 4, particularly the role of automation in the advancement of the different industrial sectors and how it would affect the construction industry. Later on, it provides the reader enlightenments about the generative design and the BIM technology.

The second chapter treats the superstructures issue and more precisely the RC dual system. The drawbacks and advantages of this system are critically discussed, then the structural constraints which control the whole design process are outlined. More in-depth reasoning of the design engineer is investigated in order to reach rational results for the later implementation of the algorithm constraints in Python.

The third chapter explains steps followed to provide the indispensable components for the optimization problem which are the search space and design variables. It begins with introducing the IFC file type, how architectural layouts are read and plotted by the program and finishes by identifying the suitable data needed especially by the TS algorithm.

The fourth chapter presents the two stages combination of two convenient approaches, Tabu Search for the moment resisting frames generation and a Genetic Algorithm for optimization of the shear walls to resist the lateral seismic load.

The fifth and last chapter goes through testing the stability of the results, tuning the weights and stopping conditions as well as justifying the needed changes to ensure the robustness. Finally, validating the results by conducting the necessary tests and comparing them to the code requirements.

Lastly, we will present the main conclusions and point out what could be improved in the future for further practicality and optimization.

Chapter 01: Industrial Revolution 4.0 in the Construction Industry

1.1 Introduction

The world has never evolved as fast as it has in the last couple of decades. To provide context, the global construction industry has been affected by the world's urban population rising by 3 million people per week, it found itself obliged to provide the cities with more infrastructures and homes. And to do so, it had continued to innovate more but not at the rate or expectations demanded of it. Therefore, we needed to consider the opportunity to radically transform our methods and approaches to construction that enable it to be more efficient and effective in adopting the technologies from other sectors and services to enable it to reshape the way our built environment assets emerge now and for the future. In following the track set by the fourth industrial revolution, the construction industry gathered pace.

This chapter will, first shed light on the different industrial revolutions and the marks they left on the construction sector. The advances of technologies that work to re-shape the construction field will be discussed along with the significant improvement that the BIM has streamlined the whole sector of the AEC.

Finally, this chapter will highlight the features of the newcomer into the field of construction, ''the generative design'' which plays a key role in solving engineering optimization issues.

1.2 Industrial Revolution 4.0

Before digging deeper into the what, why, and how of Industry 4.0, it is helpful to first understand how manufacturing has evolved since the 1800s. There are four distinct industrial revolutions that the world has either experienced or continues to experience today.

1st Mechanisation, Steam and Water Power

2nd Mass production, Assembly lines, electricity

3rd Computer & Automation

4th Cyber Physical Systems, networks, AI
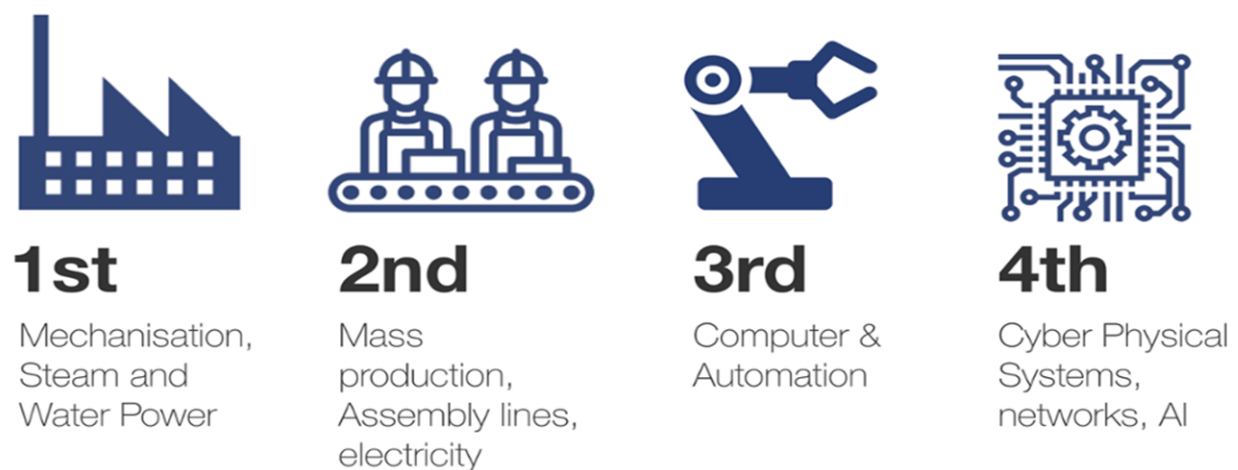
Figure 1- 1 The different phases of the industrial revolution [8]

1.2.1 The First Industrial Revolution

The first industrial revolution happened between the late 1700s and early 1800s. During this period of time, manufacturing shifted focus from manual labor performed by people and aided by work animals to a more efficient form of labor performed by people through the use of water and steam-powered engines and other types of machine tools. [13]

1.2.2 The Second Industrial Revolution

In the early 20th century, the world underwent the second industrial revolution with the introduction of steel and use of electricity in factories. The introduction of electricity enabled manufacturers to increase efficiency and make factory machinery more mobile. It was during this phase that mass production concepts like the assembly line were introduced as a way to boost productivity.[13]

1.2.3 The Third Industrial Revolution

Starting in the late 1950s, the third industrial revolution slowly began to emerge, as manufacturers began incorporating more electronics—and eventually computer—technology into their factories. During this period, manufacturers began putting less emphasis on analog and mechanical technology and more on digital technology and automation software.[13]

1.2.4 The Fourth Industrial Revolution, or Industry 4.0

In the past few decades, the fourth industrial revolution has emerged, to be known as Industry 4.0. It develops digital technology from recent decades to a whole new level with the help of interconnectivity through the Internet of Things (IoT), real-time data, automation, machine learning, access to real-time data and the introduction of cyber-physical systems. Industry 4.0 offers a more comprehensive, interlinked, and holistic approach to manufacturing. It connects the physical with the digital, and allows for better collaboration and access across departments, partners, vendors, product, and people. Industry 4.0 empowers business owners to better control and understand every aspect of their operations and allows them to leverage instant data to boost productivity, improve processes, and drive growth.[13]
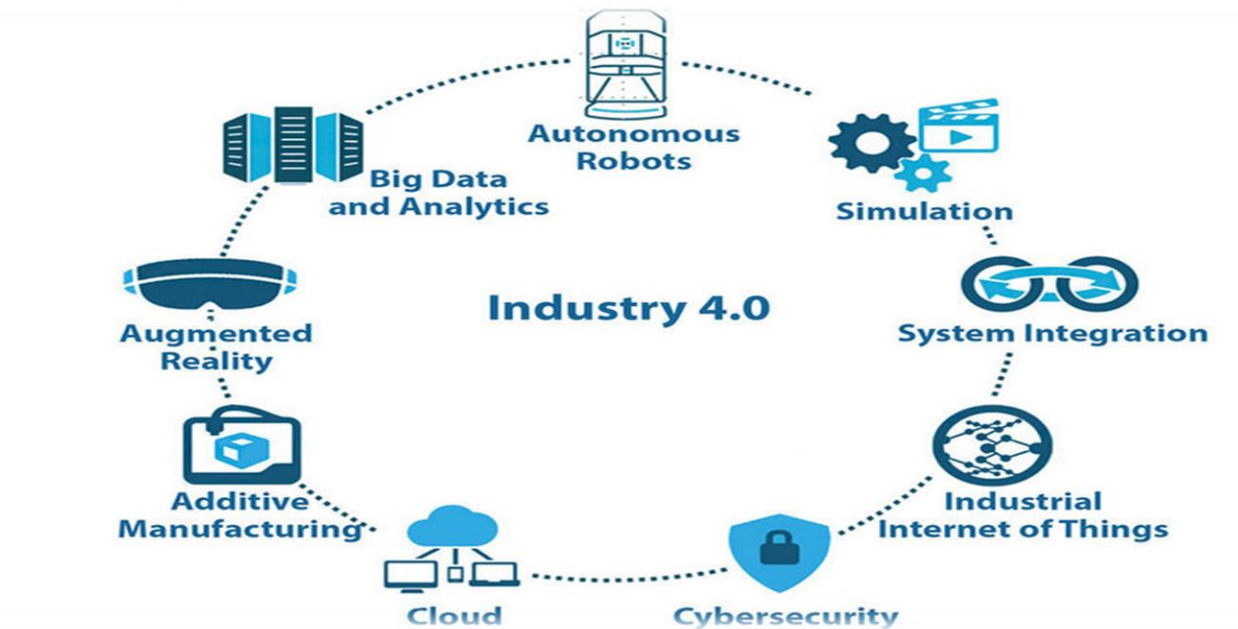
Figure 1- 2 The fourth industrial revolution [23]

1.3 Impact on Construction Industry

In the last decade, the growing use of a wide range of technologies has enabled the digitalization, automation, and integration of the construction processes over all the phases of the construction value chain. This tendency can be referred to as 'Construction 4.0'. In fact, the fourth industrial revolution, has been impacting the construction sector in a concrete manner since 2009. The development and adoption of Building Information Modeling (BIM) tools have brought planning functions closer to the actual sequence of work execution by allowing the visualization of the projected execution over time of a digital model (4D planning) and the expected costs (5D planning).

Other 4.0 technologies are characterized by connected systems of sensors, intelligent machines, mobile devices, and new software applications. For example, advanced digital technologies now include the use of drones to survey and inspect construction sites. New additive manufacturing methods, such as 3D printing, are applicable to large-scale building components. Also, 3D scanners can be used to create digital models of complex buildings, while Global Positioning System (GPS) and Radio Frequency Identification (RFID) can be used to track materials, equipment, and workers. However, in practice, Construction 4.0 does not correspond solely to the use of new or existing technologies in the field of construction. The concept of Construction 4.0 also implies a comprehensive and profound transformation of the project management processes of construction firms through the use and exploitation of data collected in real time using new or existing technologies for decision-making purposes. These processes need to be studied to favor the valorization of relevant information captured using 4.0 technologies at all phases of a project's life cycle with the aim of exploiting such information in real time and afterwards. The main uses of these 4.0 technologies and the applications associated with them also need to be studied in order to show their utility in the construction industry.[23]

1.4 Building Information Modelling

One of the biggest industries that impact our daily lives is the construction sectors. Without it, there would be no roads, offices, hospitals and perhaps most importantly, homes. The industry represents the building blocks of our communities and, from a wider point of view, is a cornerstone of the economy. Ever-growing demand means the sector not only has the potential to create jobs and boost the economy, but to facilitate the growth of other industries, including energy and maritime, by laying the foundations for infrastructure, sites, and offices, among other things.

In recent years, the construction industry has faced several challenges: Climate change, sustainability, lagging productivity, financial pressure, and others.

In order to overcome difficulties, digitalization technology was implemented in construction sector. Consequently, a significant improvement was achieved in productivity. The digital tools used have been designed to be adapted to the needs of the construction industry: design, construction, and operation. However, the massive and continuous data transfer throughout the construction process between AEC stockholders (Architecture, Engineering and Construction) requires strict control and compatibility in order to avoid any losses that can cause fatal errors and delays during project execution. Generally, the exchange of information is done in the format of drawings (plan views, horizontal and vertical sections, detailed views, etc.), where the software's used to produce this data are almost limited to a simple two-dimensional (2D) presentation. It is through the development of the field of information and technology (IT) in terms of tools and programs, that a new approach has entered the field of this industry, known by "three-dimensional modelling". It allows the description of a building in 3D format. Since, users have invested in further improving the functionality of this type of modelling, and thus widening the scope of its exploitation. Building information modelling (BIM) is one of these latest emerging technologies used in the construction design industry that facilitates access to the data exchange in order to enhance communication among all the project stakeholders AEC. In Addition, BIM technology has already begun changing the working philosophy between the designers and their consultants and builders, as well as the ability to guide the construction industry into a more economical and environmental aspect.

1.4.1 Definition of BIM

Building Information Modeling (BIM) is a revolutionary technology that has quickly transformed the way buildings are conceived, designed, constructed and operated.

While there are different definitions of BIM, there is a common consensus that BIM is an emerging approach to the design, analysis, and documentation of buildings. At its core, BIM is about the management of information integrated from many sources that evolve in parallel with the real project throughout the entire life cycle of a design process, from early conceptual design through construction administration, and even into facilities management.

In the past, during the construction phase, many problems and errors occurred due to shortcomings from the design phase. Similarly, many difficulties in communication, coordination

and standardization face the industry. Hence, communicating design information effectively, contributes to overcoming these interoperability issues. In a traditional process, documents and drawings are communicated between project partners, making a new file each time the file is shared. However, in BIM, the model serves as a database, where information is supplied and pulled out on demand, as following figure depicts:
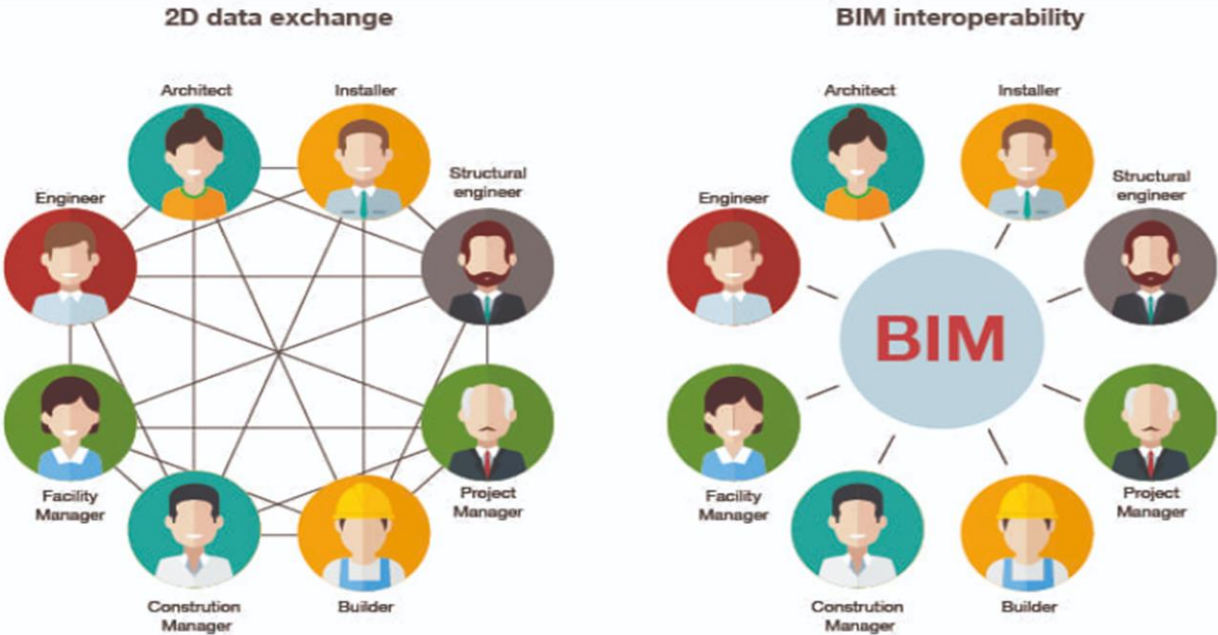
Figure 1- 3 Before and after BIM technology [6]

1.4.2 BIM Dimensions

BIM allows for the development of models at several levels of information, namely: The 3D model, which is the process of gathering graphical and non-graphical information, 4D model that is attached to the 3D model and adds the aspect of time, 5D model that includes the parameters of cost as well as supplies, 6D & beyond models which take into consideration the different aspects such as the management of the installations, as well as their environmental impacts.[4]

The following figure depicts the connection between the different dimensions. (Figure 2-3)
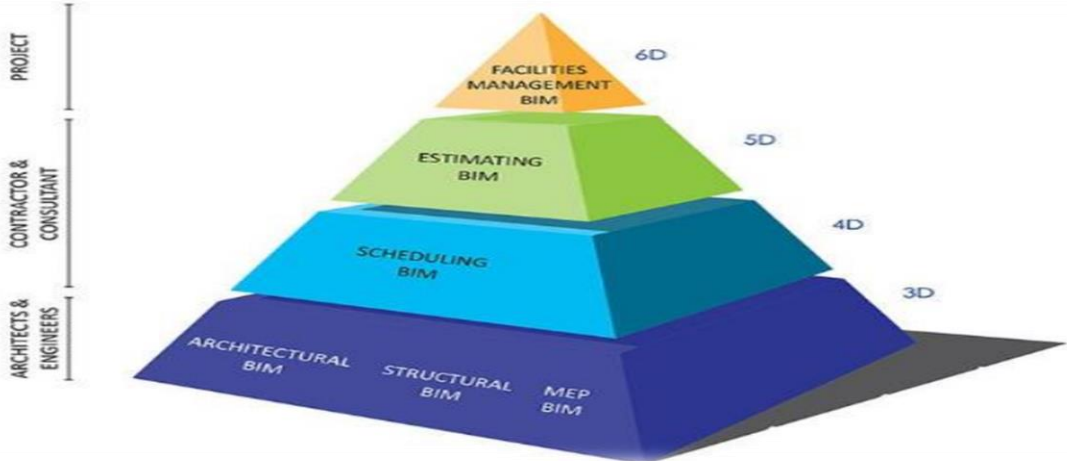
Figure 1- 4 BIM dimensions during the construction project [4]

1.4.3 BIM Maturity Levels

BIM adoption is progressive, and often described as a 'journey'. The milestones on that journey are the BIM Levels. The concept of 'BIM Levels' has become the common definition of the criteria required to be deemed BIM-compliant. [26]

there exist different levels of shared collaboration in a construction project. There are four distinct BIM maturity levels, a brief explanation of each one separately below:

Level 0 BIM: In its simplest form, level 0 effectively means no collaboration. Only 2D Computer-Aided Design (CAD) drafting is utilized; mainly for Production Information. Output and distribution are via paper or electronic prints, or a combination of both.

Level 1 BIM: This typically comprises a mixture of 3D CAD for concept work, and 2D for drafting of statutory approval documentation and Production Information. CAD standards are managed to a specific code, and electronic sharing of data is carried out from a common data environment (CDE), often managed by the contractor.

To achieve this Level 1 of BIM, the following requirements are to be met:

- Roles and responsibilities should be agreed upon.
- Naming conventions should be adopted.
- Arrangements should be put in place to create and maintain the project specific codes and project spatial coordination.
- A "Common Data Environment" (CDE) for example a project extranet or electronic document management system (EDMS) should be adopted, to allow information to be shared between all members of the project team.
- A suitable information hierarchy should be agreed which supports the concepts of the CDE and the document repository.

Level 2 BIM: Level 2 BIM is distinguished by collaborative working and requires "an information exchange process specific to the project in addition to coordination between various systems and project participants" Any CAD software used by that each party must be capable of exporting to one of the common file formats such as IFC (Industry Foundation Class) or COBie (Construction Operations Building Information Exchange). This method of working has been set as a minimum target by some governments for all work on public-sector work.

**Level 3 BIM:** Level 3 anticipates the following 'key measures' to be secured:

- The creation of a set of new, international 'Open Data' standards which would pave the way for easy sharing of data across the entire market.
- The establishment of a new contractual framework for projects which have been procured with BIM to ensure consistency, avoid confusion, and encourage, open, collaborative working.
- The creation of a cultural environment which is co-operative, seeks to learn and share.
- Training the public sector client in the use of BIM techniques such as, data requirements, operational methods, and contractual processes.

Driving domestic and international growth and jobs in technology and construction.

The next figure will summarize the 4 BIM maturity levels.
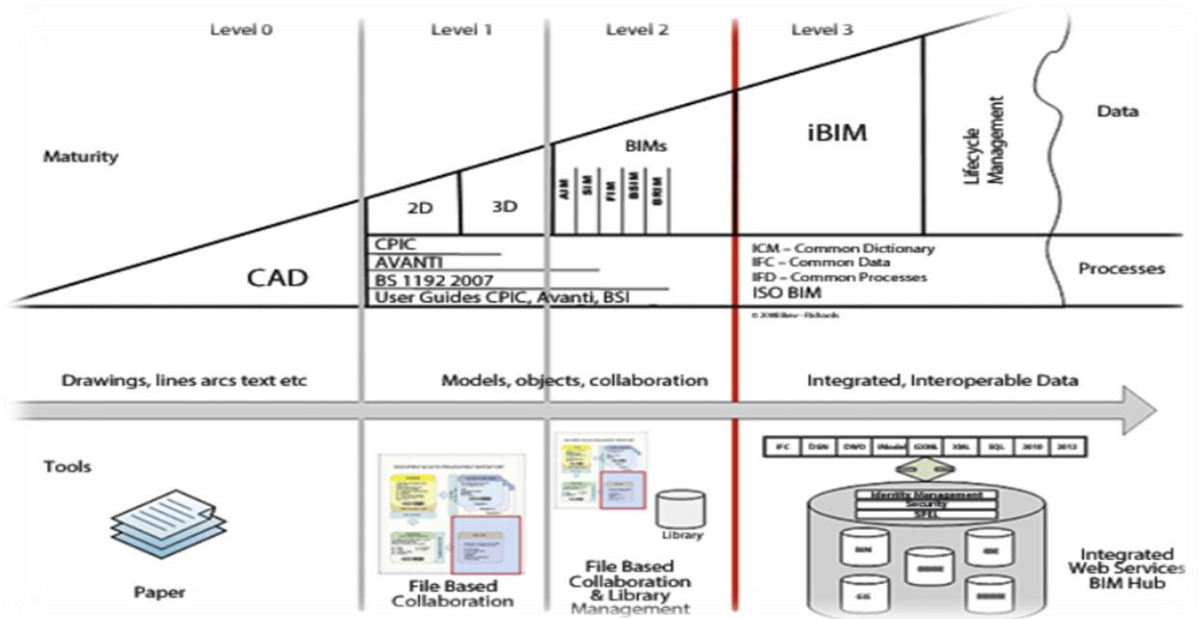
Figure 1- 5 Maturity levels of BIM [4]

A non-exhaustive list of benefits of using BIM is:

1. Improved communication and teamwork.
2. Cost assessment based on the project model.
3. Monitor changes.
4. Project visualization during the planning stage.
5. Effective clash detection and collaboration
6. Lower expenses and risk
7. Superior sequencing and scheduling.
8. Improved work productivity and prefabrication.
9. Highly secure development sites.
10. Improved structures.
11. Lowering the entire duration of the project.
12. A more grounded management of the faculty and structure rendition.

1.4.4 Interoperability of BIM

Interoperability is a characteristic of a product or system, whose interfaces are understood, to work with other products or systems, present or future, in either implementation or access, without any restrictions. The term interoperability is used to describe the exchange data capability between the different programs through a common set of file formats, that allows the reading and writing of information using the same protocols. One common use case for software interoperability is for the customers freedom to switch from one product to another while keeping the data intact after the transfer. This is especially important for cases where data stays in a single system over a long time. The interoperability parameter plays a leading role in the

construction industry between the different partners AEC, where the data exchange is done in a centralized and a safe BIM platform, ensuring the share of the information and data generated at one time to be usable without a new re-entry for other phases.

In order to guarantee effective interoperability between AEC players, several open and standardized file formats have been produced and invested in by researchers as well as institutions in the building industry. Among the standardized formats:

- **IFC**: Provides a framework for organizations to produce interoperable software to exchange information on building objects and processes to creates a language that can be shared among the building discipline.
- **XML**: Set of rules for designing text formats to structure information. XML supports data transactions between different software applications, leading to a better way to communication of information.
- **gbXML**: is the most widely supported data format for the exchange of building information between BIM/CAD and energy performance applications.
- **BIMXML**: an XML schema developed to represent a simplified subset of BIM data for web services.
- **IDM**: Information Delivery Manual, the business case specification for exchange BIM data, including end user Exchange Requirements.
- **RVT**: This is Autodesk's proprietary format for Revit files. These can vary significantly in size depending on the level of development. They can only be opened in Revit.
- **BCF**: BIM Collaboration Format, an XML schema that encodes messages to enable workflow communication between different BIM software tools.
- **IFD**: Describes what kind of information is exchanged by providing a mechanism that allows the creation of unique IFD IDs, to connect information from existing databases to IFC data models.
- **DWF**: Design Web Format, originally developed by Autodesk, as a PDF alternative for CAD data/documentation.
- **PDF**: Portable Document Format originally developed by Adobe for the electronic exchange of any printable document.
- **OGC**: Open Geospatial Consortium, international industry consortium for developing standards for geospatial data-enabled technologies. [4]

NOTE: We have chosen IFC format as it is the most practical in the BIM environment and because it is supported by the software programs, we used such as REVIT and ETABS.

1.4.5 BIM Platforms

BIM software is widely used by many construction businesses (big and small) especially in the AEC sectors. So, there is a plenty of BIM software solutions available: [4]

- **Autodesk BIM360**: is a cloud-based web service that provides teams access to data to improve decision-making and avoid expensive delays.
- **Autodesk Revit**: It is one of the most popular software packages developed by the CAD giant Autodesk. It is developed to be used by all the AEC actors, such us, architects, civil engineers, drafters, mechanical, electrical and plumbing (MEP) & Electrical engineers, contractors, and landscape architects, among others.

- **Tekla structure**: famous product competing with Autodesk. It is an easy and efficient program -to- use, leading the same functions as Revit.
- **Navisworks**: is also built by Autodesk. The difference between Navisworks and Revit is that Navisworks functions as a project review software tool for AEC professionals.
- **Tekla BIMsight**: leading the same functions to Navisworks, but especially for the Tekla models, actually replaced by Trimble connect.
- **Trimble Connect**: is a cloud-based platform that specializes in connecting the right data to the right people at the right time. This solution is designed for architects, engineers, general contractors, subcontractors, and owner-operators. It brings people, technology, and information together in an environment that empowers collaboration.
- **BIMobject**: is a BIM content open-source platform. It is a cloud solution used by architects, engineers, contractors, and designers to access manufacturer-specific BIM objects.
- **BIMx**: is a collection of desktop and mobile software tools to present BIM models in 3D models and 2D documentation. The integrated 2D and 3D building project navigation bridge the gap between the design studio and the construction site.
- **ArchiCAD**: is a 3D architectural BIM tool for design and modelling. it is used by urban planners, architects, and designers to enhance their design workflow processes.
- **Vertex BD**: is a BIM platform for Cold formed steel frame.

1.4.6 Description of Autodesk Revit (platform used in this study)

Autodesk Revit is a Building Information Modelling (BIM) software offering a multi-disciplinary and collaborative approach to design and construction projects. Revit empowers architecture, engineering, and construction professionals to produce consistent, coordinated, and complete model-based designs for buildings and infrastructure. By unifying powerful tools for architecture, MEP, and structural engineering into a single interface. Revit also has extensive uses. The efficient use and designing of Revit have led to the creation of exceptional models and projects still known to the world. Revit software would help produce exceptionally well-coordinated, consistent, well-compiled building structures and designs as well as documentations which are mostly model based; Revit is an extremely viable option for 3-D viewing of different sections of the architecture; It makes use of 3D visualizations to have an idea of the buildings it will be growing in the near future. Since, it is essential to have a clear idea about the construction process. It is recommended for its extensive use of tools that enhance architectural and structural designs. Revit has been used across multiple disciplines with its use of work-sharing that share projects by dividing around work across various disciplines. The workflows could also be enhanced immensely with regional solutions, which could be customized as per third-party partners. Revit could also be used to connect various teams as well as data on singular projects on the BIM 360 platform.[4]

1.4.7 Families in Revit

There are three different types of families in Revit, the system family, the component family, and in-place family. In this section we will discuss the difference between them

1.4.7.1 System family

System families contain family types that we use to create basic building elements such as

- Ceilings
- Curtain Systems
- Curtain Wall Mullions
- Floors
- Fluids
- Model Text
- Railings
- Ramps
- Roofs
- Stairs
- Structural Columns
- Structural Foundations
- Structural Framing
- Walls

System families also include project and system settings, which affect the project environment and include types for elements such as levels, grids, sheets, and viewports.

System families are predefined in Revit and saved in templates and projects, not loaded into templates and projects from external files. System families cannot be created, copied, modified, or deleted, but the types within system families can be duplicated and modified to create custom system family types. All but one system family type may be deleted in a system family, because at least a single type per family is required to create new system family types. [31]

1.4.7.2 Component Families

Component families (sometimes called standard families) are created outside of the project environment; still belonging to Revit, but in a specific environment called the Family Editor. Component families have their own file format extension (.rfa) and can be stored or edited as separate files independent of a model, and then loaded at any time into a project. To create a new component family, either a duplicate is made then modified it in the Family Editor or a new one is created in the Family Editor, using the family templates included with each copy of Revit.

An important advantage to using Revit is that it does not require knowledge of any programming or scripting language to create new, smart, parametric families [31]

1.4.7.3 In-Place Families

In-place families are custom objects that are specific to a certain context within a model. A complex railing fence on a site is an example of an in-place family. These families use the same functionality available in the Family Editor but are made available in the context of a project file.[31]

1.4.8 Converting 2D Drawings into a 3D BIM Model

Usually when working on a project, two-dimensional plans, sections and elevations that are already available in it will be used as the basis for creating a 3D building information model. Revit provides flexibility to incorporate old materials into the model and allow data to be imported from multiple file Formats (DWG, etc.). The development and adoption of smart software means redrawing will no longer be a necessity as Revit provides a way to maximize reuse and refer to existing data.[31]

Revit objects can be created in three ways:

• **Drawing**: The default mode for all Revit tools that requires the user to draw objects is the Drawing mode. The shape of the object can be created using standard drawing options in this mode.

• **Picking references** (lines) out of which the object can be created: Instead of manually drawing, this option allows the user to create elements by picking references. It helps to draw and then convert any line of an imported drawing into an object.
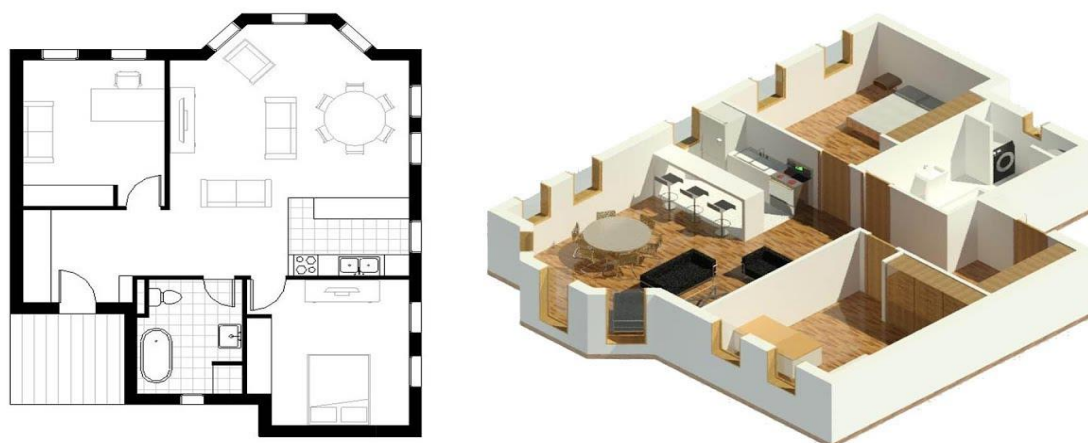
• **Picking a face**

Figure 1- 6 From 2D to 3D BIM model

1.4.9 Used Building models

- Model 1:
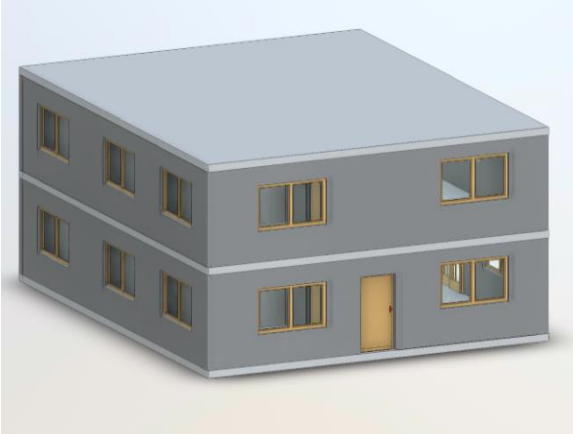
Figure 1- 7 3D view
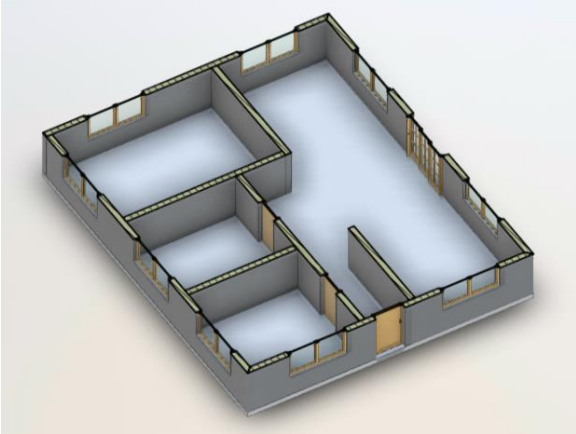
Figure 1- 8 Floor plan 3D view

- Model 2:
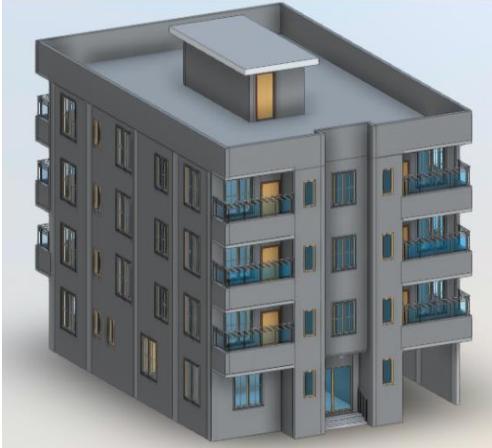
Figure 1- 9 3D view
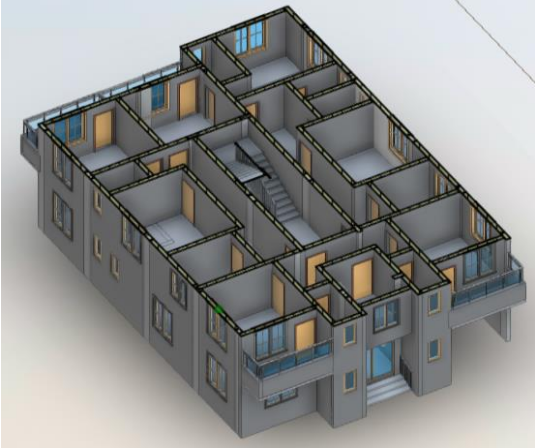
Figure 1- 10 Floor plan 3D view

- Model 3

Figure 1- 11 3D view
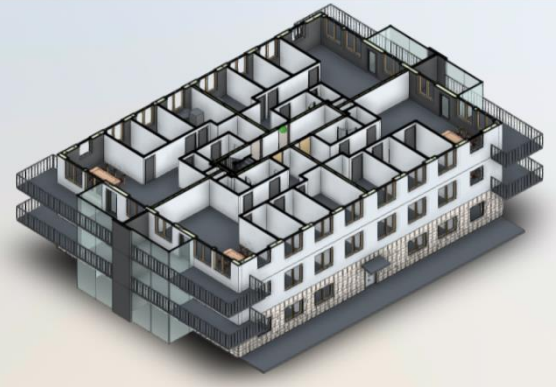
Figure 1- 12 Floor plan 3D view

1.4.10 BIM and Revit for reinforced concrete

Building Information Modeling (BIM) is a critical part of how structural building and infrastructure systems are designed and built today, but the reinforced concrete industry has been lagging behind structural steel when it comes to its adoption of BIM. This is due to the highly fragmented nature of its supply chain which requires a number of different designers and suppliers to collaborate and simultaneously deliver the final product.[25]

The BIM tools help engineers in four main ways:

1. Combining the versatility of 2D documentation with the higher level of fidelity and accuracy of 3D modeling of steel reinforcement and concrete accessories, with minimal effort to produce either.

2. Allowing users to design and detail with clash prevention in mind; both in the preconstruction and site execution project phases.

3. Enabling the transition from design to detailed models while respecting both perspectives, following local code requirements, and automating the process of making changes so they are less disruptive to the design process.

4. Increasing transparency and quality of the model information being used from bidding to procurement by not only providing quantifiable information, but also enabling access to it in collaboration friendly environments.

An example on how to represent reinforcement in a concrete element is given here:

✓ From the window that appears, go to the **Ribbon**, and select ''**Architecture**'' Tab.
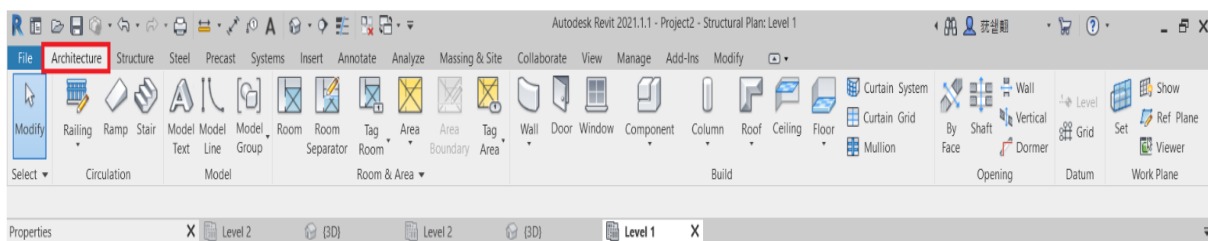
Figure 1- 13 Architecture tab

- ✓ From the **Build-Panel** choose the **Split Button '' Column ''** then select **Structural Column.**
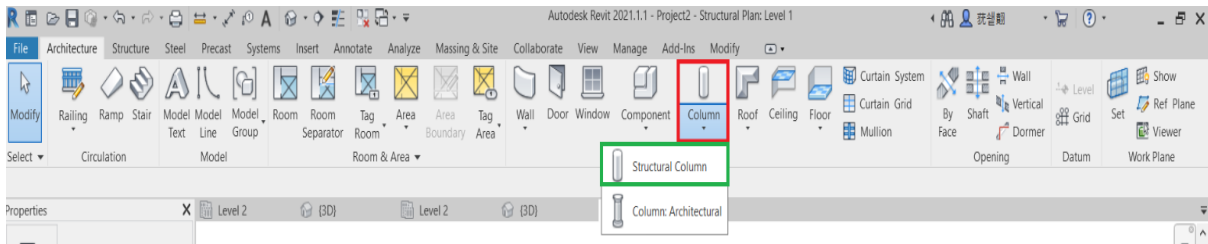
Figure 1- 14 Selecting the column

- ✓ After creating the column, click on it to get the **Rebar** Button above.

Figure 1- 15 The rebar option

- ✓ Start off the reinforcement with the **rectangle-like** shaped Rebar.
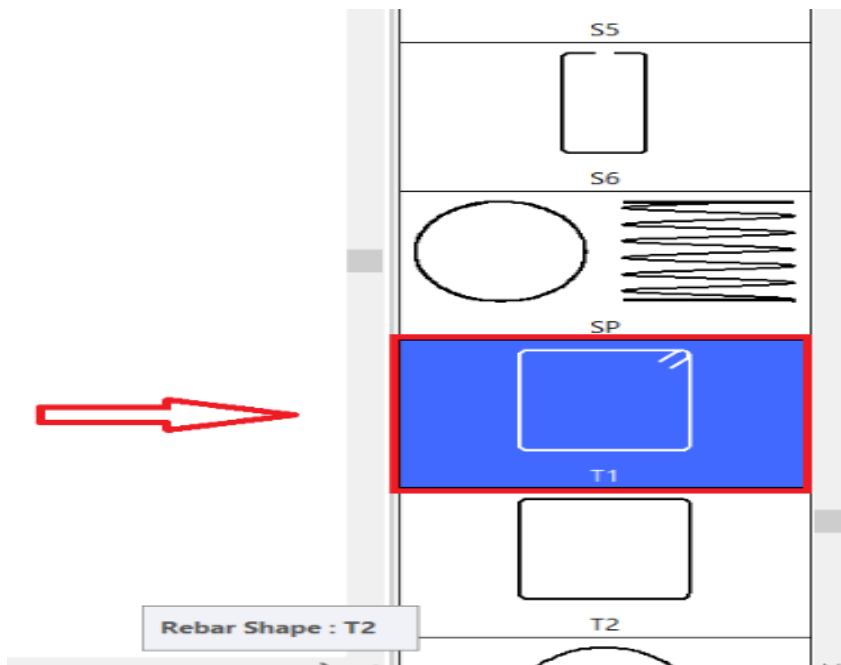
Figure 1- 16 The rectangle-like rebar

✓ In the 3D view, we click on the rebar then we change the **spacing parameters** to what we need.
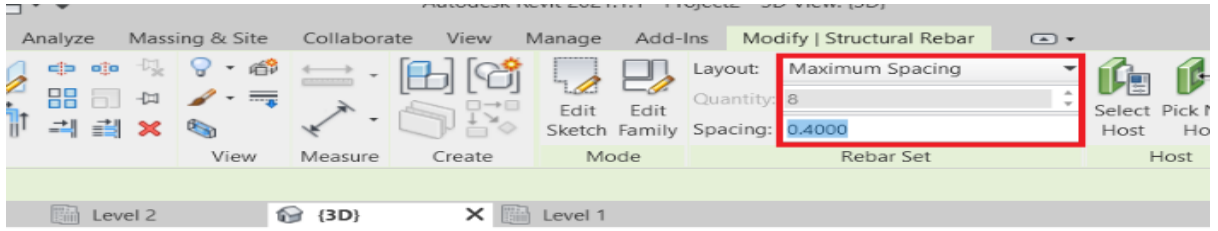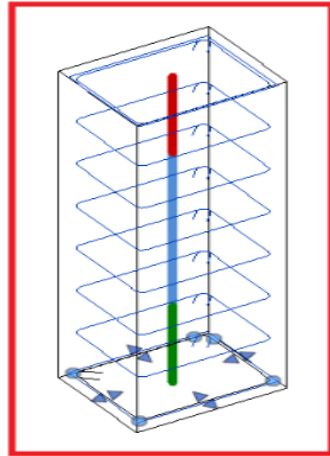
Figure 1- 17 The spacing parameters

✓ Next step is to insert the vertical rebars, with the attention of selecting the **perpendicular to cover** option.
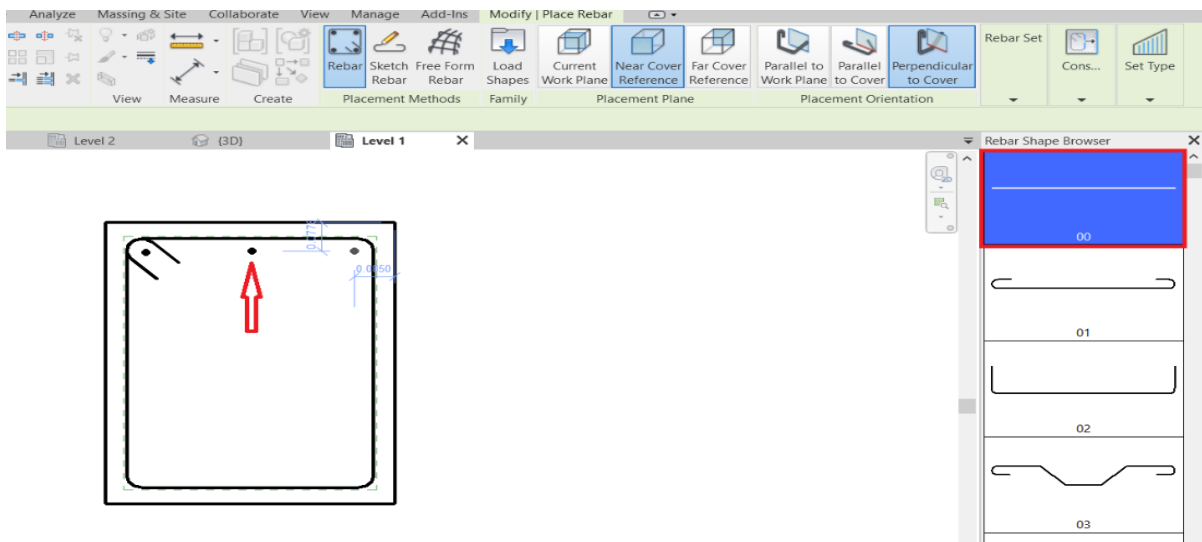
Figure 1- 18 The vertical rebar

✓ Eventually, the resulting **reinforced column** will look like that.
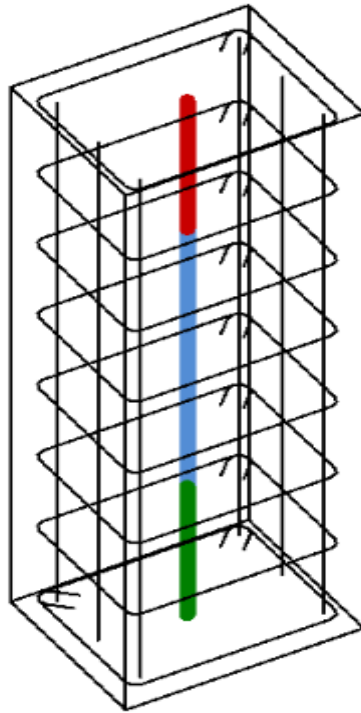
Figure 1- 19 A reinforced Column in Revit

1.5 Generative design

1.5.1 Definition

Generative design is an iterative design exploration process that uses an AI-driven software program to generate a range of design solutions that meet a set of constraints. Unlike traditional design, where the process begins with a model based on an engineer's knowledge, generative design begins with design parameters and uses AI to generate the model.[33]

By modifying the design parameters in an increasingly refined feedback loop, engineers can find highly optimized and customized design solutions to a wide range of engineering challenges, such as making product components lighter, stronger, and more cost-effective.

Generative design is a definitive shift in how to conceptualize, design, and build. At its core, generative design is a strategy that augments human capabilities by using algorithms to automate design logic. The design parameters must still be defined, but instead of modeling one thing at a time, generative design software helps create many solutions simultaneously and occasionally find "happy accidents" or unanticipated and unique solutions that would be difficult to discover with traditional methods. The change now is that scripting and algorithms control much larger chunks of functionality and can manage much bigger swaths of data and analysis.

1.5.2 The Changing Role of the Engineer in Generative Design

The role of the engineer has evolved alongside technology. As design has come to rely more heavily on computer software, understanding how to manipulate digital tools to solve design challenges has become a central requirement for engineers working in all industries. Before generative design, engineers would conceptualize and test iterations using hands-on sketching and modeling.

Now, using generative design software, engineers specify high-level performance requirements and general design frameworks and then relegate the details to the software. The process of defining these parameters can be particularly complex when characterizing novel materials or modeling hard-to-define problems and solution spaces.

In a fundamental shift from traditional design processes, engineers will no longer need to create design solutions themselves. Instead, through generative design, they articulate and refine the environment in which design solutions can succeed. By letting computers do the "thinking," generative design lets engineers focus on innovation and high-level problem-solving.

1.5.3 Progression from Traditional to Generative Design

The design technology in the AEC Industry is progressing towards the generative design model. The biggest difference can be seen in the mindset of a designer.[33]
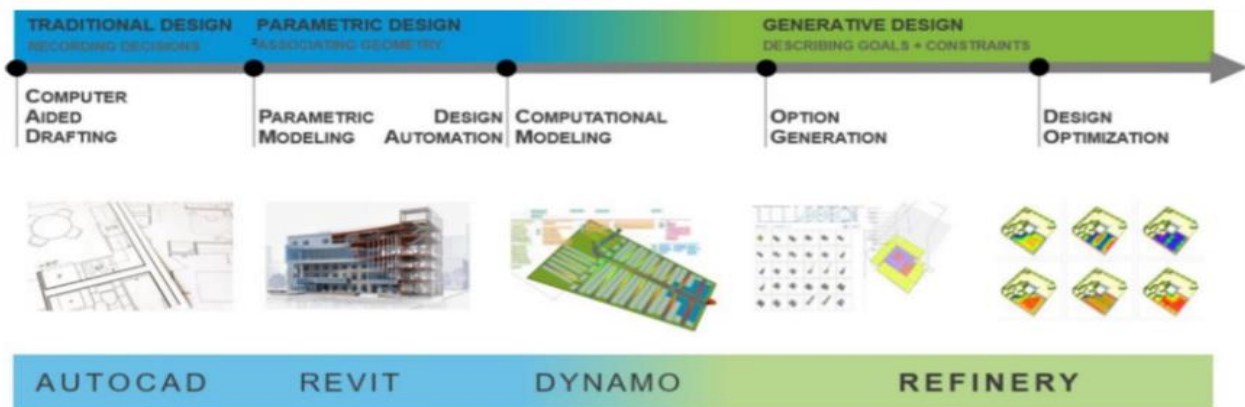
Figure 1- 20 Progression from Traditional to Generative Design [31]

In **Traditional Design** a designer uses basic techniques like sketching to describe an idea. For example: "Drawing of a wall with a door in it." With AutoCAD the designer can apply Computer Aided Drafting.

In **Parametric Design** the user defines relationships between traditionally drawn or sculpted elements. For example: "This door depends upon this wall and will move with it."

Contrast this with the traditional CAD environment, where each point, line, text, etc. has no relationship to any other. In the parametric design environment changes to one piece of data

creates changes in other pieces of data. Generally, these systems are limited by the ability to make direct relationships. In the building industry, Revit can be used for this task.

With **Design Automation** the user gains the ability to automate tasks within parametric models, by driving the parameters with automated scripts. For example: "Create a door for every x meter of a wall."

The geometry and data are outcomes of the automatic execution of a set of rules and can use traditional modelling elements as inputs. This technique is a level of abstraction from parametric modelling where arbitrary pieces of data are related to others. Typically, this can be done with Revit and Dynamo.

In **Computational Modelling**, the user explicitly describes a process to create a design outcome. For example: "Create a number of doors in the wall and evaluate how many exits per unit length."

This method is very close to design automation, except for that here, the possibility to evaluate the design outcomes exists. It is a generalized way to create data as well as relationships between data. The kinds of relationships that can be defined are versatile (if-then-else, looping, recursive) and users can create more customized reactions to changes in the system.

With **Option Generation**, the user can explore variations of computed rules given different starting points for the calculations. For example: "Show me all the valid places a door could be placed on this wall."

Given a Parametric Model or Computation environment, there is an infinite number of variations for changing and combining inputs. The results are not distinguished based on one being any better than another. The user is given an opportunity to sort and choose.

With **Design Optimization**, the user defines explicit goals and a computational or parametric model is automatically explored for states that fit those goals. For example: "Find the valid places where doors on this wall are closest to exits."

Given a Parametric Model or Computation environment, display the examples of possible states of the model that have certain desirable characteristics.

Ultimately, with **Machine Learning** (ML), the user states outcomes and the system returns conforming results based on historical data. For example: "Lay out interior doors for a hospital egress."

Given a desirable set of characteristics, generate a design or a set of designs that fit the description. Instead of starting from a parametric or computational model, ML-based tools use large "learning" data sets where the computer finds patterns that are inferred instead of being explicitly stated.

1.5.4 Generative Design Process

Generative design allows for a more integrated workflow between human and computer, and as a result both are required to undertake a series of steps that allow the process to take place. These steps can be categorized into the following stages: generate, analyze, rank, evolve, explore, integrate.[33]
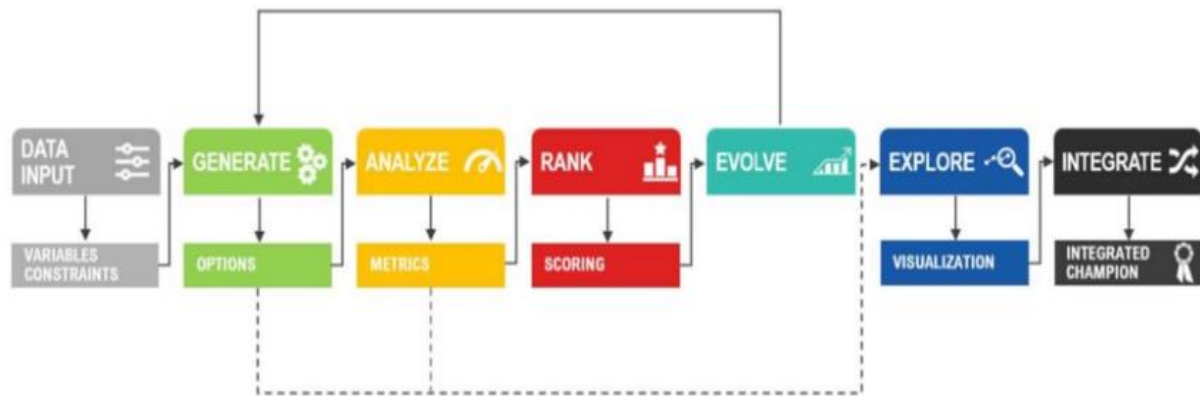
Figure 1- 21 Steps of the generative design process

Generate

This is the stage at which design options are created or generated by the system, using algorithms and parameters specified by the designer.

Analyze

The designs generated in the previous step are now evaluated on how well they achieve goals defined by the designer.

Rank

Based on the results of the analysis, design options are ordered or ranked.

Evolve

The process will use the ranking of the design options to figure out in which direction designs should be further developed or evolved.

Explore

Generated designs are explored and compared by the designer, inspecting both the geometry and evaluation results.

Integrate

After choosing a design option, the designer integrates this design into the wider project or design work.

1.5.5 Software Tools for Generative Design (for construction and other sectors)

a) **Fusion 360 from Autodesk:** Fusion 360 offers users a powerful set of modeling tools, including sketching, direct modeling, surface modeling, parametric modeling, mesh modeling, rendering, and much more. Its generative design capabilities enable users to identify design requirements, constraints, materials, and manufacturing options to generate manufacturing-ready designs. All the while allowing the leverage of machine learning and AI to review cloud-generated design outcomes based on visual similarities, plots, and filters. [33]

b) **Creo Generative Design from PTC:** Leveraging the cloud, this software enables users to create optimized design concepts and simultaneously explore and test numerous design iterations quickly. It highlights the iterations that best match a user's objectives based on the design parameters set. Within the Creo design environment, this software promises to generate high-quality, lower-cost, and manufacturable designs, effectively.

c) **nTop Platform from nTopology:** The nTop Platform software promises users complete control over every aspect of the optimization process and its outputs. Leveraging advanced generative tools, users can create custom, reusable workflows tailored to an application's unique requirements. Featured capabilities of this program include unbreakable modeling and latticing operations, topology optimization, reusable design workflows, field-driven design, and mechanical-thermal finite element analysis simulations.

d) **NX from Siemens:** Beyond generative design, the main feature that NX offers is the digital twin technology, which promises users a flexible, powerful, and integrated solution to help them streamline the design and delivery of better products. NX combines design interoperability, validation, model-based definition, and more to help users move products through research and development faster and at lower costs while improving product quality.

e) **MSC Apex Generative Design from MSC Software:** This program promises users an end-to-end solution for making high-precision metal components more quickly and with less human intervention than its competitors. MSC Software reports that users experience reductions in initial design and setup time by as much as 80 percent. The software combines simplicity, automated design, import and validation, and direct output in one process.

f) **Archistar:** Archistar is a comprehensive property development platform that simplifies many aspects of development projects. Generative design is one of its focal points.

It provides a wide range of unique designs based on experimental values or local planning documents.

Currently, Archistar can generate designs for the following:

- Apartments
- Townhouses
- Terrace Houses
- Manor Houses
- Duplexes
- Subdivisions

- Commercial buildings
- Hotels
- Mixed-use property

In addition, Archistar's analytics engine can assess mid- and late-stage factors, like building separation, sunlight, and cross-ventilation.

Moreover, designs can be extracted to any CAD programs, then refined until they conform to the standards.

Others features include auto feasibility, branded reports, contextual design, and more. Such a broad spectrum makes Archistar the preferred platform of many architects.

1.5.6 Benefits of Generative Design

The experience of the designer or the engineer remains the most essential element in the design process, indeed, the ability to analyze design problems and to identify driving factors that play a major role towards the achievement of a high-quality result remains a human strength that cannot be easily mimicked by AI and the generative design tools. Nonetheless, the latter offers several services and benefits that can ease tasks and optimize solutions.

Simultaneous exploration: A notable benefit of generative design is that it allows the simultaneous exploration, validation, and comparison of hundreds or thousands of design options. The software can display and compare design options in a way that enables engineers to quickly and efficiently find what best meets a project's parameters and needs.

Accelerated design timeline: When engineers leverage AI to discover and test new complex design iterations quickly, efficiently, and at scale, they can drastically shorten research and development timelines for new products. As a result, companies utilizing generative design gain a competitive edge in accelerating products' time to market.

Leverage advanced manufacturing processes: Generative design can create complex designs like organic features and internal lattices to leverage the unique design freedom offered by additive manufacturing technologies. It also offers the ability to consolidate parts, so a single complex geometry created by a generative algorithm and 3D printed can replace assemblies of dozens of separate parts.

1.6 Conclusion

Although it is one of the oldest and longest-standing industries, the construction sector is still struggling to integrate new technologies. The construction industry suffers from low level of automation and digitalization. The fourth industrial revolution 4.0 has introduced digital technologies, sensor systems, intelligent machines, and smart materials to the construction industry where BIM has become the central repository for collating digital information about a project solving a past problem where the construction industry had a large volume of data sets that were at risk being partially lost. Moreover, the use of generative design helped in obtaining optimized solutions leading to time and cost savings. In this context, an intelligent approach is investigated in the next chapters to move forward the structural design towards automation.

Chapter 02: Definition of the Design Optimization Parameters of RC Dual Systems (RCDS)

2.1 Introduction

Damages of earthquake loading to structures are inevitable. Nevertheless, Civil engineers didn't sit and wait for some miracles to happen. Instead, they tried new approaches and came up with design ideas to diminish the ruin, assure the stability of structures and the safety of habitants at once.

So, along the journey of civil engineers trying to explore new options to step up their game against these disasters, they could originate some superstructure types which could efficiently mitigate the earthquake actions.

This chapter will shed light on these different types of lateral resisting systems and more specifically the RC dual systems. Furthermore, it will discuss what should be taken into consideration before deciding to choose this system and how to optimize it later.

2.2 Types of Lateral Resisting Systems

Most commonly used reinforced concrete structures for multistory buildings are of three types:[21]

- Frames
- shear wall systems
- Dual systems.

The selection of structural system for a building is primarily determined by the function and architectural considerations, by the total height of the building and by the seismic exposure.

2.2.1 Reinforced Concrete Frames:

Frames for buildings are spatial (3D) systems of beams and columns rigidly interconnected in joints.
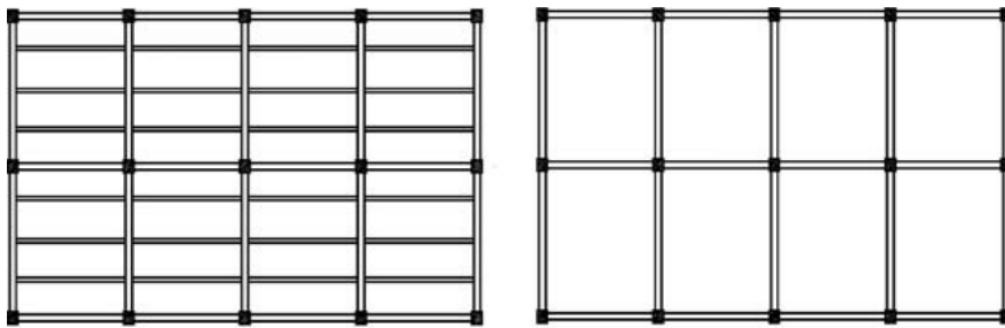
Figure 2- 1 General configuration of a frame structure
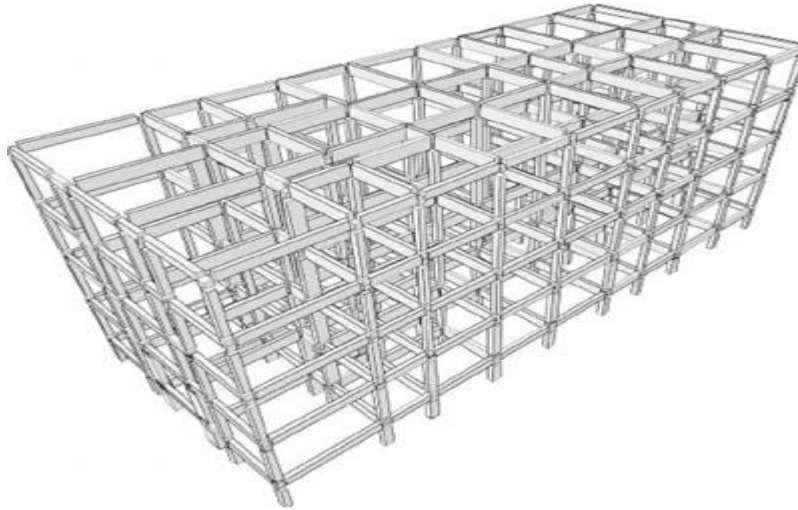
Figure 2- 2 3D view of a frame system

The structural configuration and proportions, methods of analysis and design are strongly influenced by the building seismic exposure. According to this criterion, broadly, two types of frames exist:

• Frames of buildings situated in non-seismic or very low seismic areas ("non-seismic frames'')

• Frames predominantly designed to resist seismic actions.

General layout of moment resisting frames have the columns disposed in a rectangular regular mesh. Spans and bays are chosen according to architectural and functional requirements. This means that the cells determined by four columns should fit generally with the requirement of column free room. Generally, span and bay lengths are less than 5.00 m for residential buildings. For office buildings or other similar facilities like hospitals, spans can be as much as 9.00 m or even longer. There are also special framed structures for show buildings (cinema, theaters, opera) or similar. When subjected to lateral forces, the building acts as a vertical cantilever. The cantilever effect generates important global shear forces and overturning moments, which has to transfer them to the foundation soil.[21]

2.2.2 Shear wall Systems:

Multi-story frame structures subjected to seismic actions have a limited use for Highrise buildings due to large columns' sizes required at lower storeys Search for alternative structural solutions, based on use of vertical elements with high stiffness and resistance, was a condition for extending the reinforced concrete structures for high- and super-high-rise buildings. One of the most important solution, was the use of structural walls as an alternative solution to the traditional frame structures. The idea was to convert partitions into structural walls. Due to their cross-section shape and proportions, the walls have a high "natural'' stiffness and a substantial resistance capacity.[21]

Types of Structural Walls

An ideal solution for structural walls is that of compact solid units called cantilever walls (Fig 2-3). Cantilever walls are easy to be executed and lead to structures with unambiguous load paths. The most suitable cross section for cantilever walls is rectangular having or not reinforced boundaries. More solid walls provided on perpendicular directions are sometimes crossed forming elements with different section shapes: T, L or tubular.

In many situations, openings in structural walls are required to accommodate doors or windows. We call the resulting component structural wall with openings. When openings are provided in uniform regular pattern over the wall height the unit can be considered to be formed by two or more solid cantilever walls coupled through rigid beams (Fig 2-4). These are coupled structural walls. Besides functional advantages (in comparison with cantilever walls) the coupled walls, appropriately designed and detailed, showed a stable, controllable energy dissipating capacity during high intensity earthquakes. Sometimes, a staggered pattern of opening is preferred. When openings are suitably arranged, with large space between them, the wall has a good stiffness and appropriate reinforcement can be provided to be effective in preventing shear cracks. Both cantilever and coupled walls can be performed by cast-in-place or by prefabricated concrete. Inter-connected rectangular prefabricated units called large panels, realize prefabricated structural walls. [21]
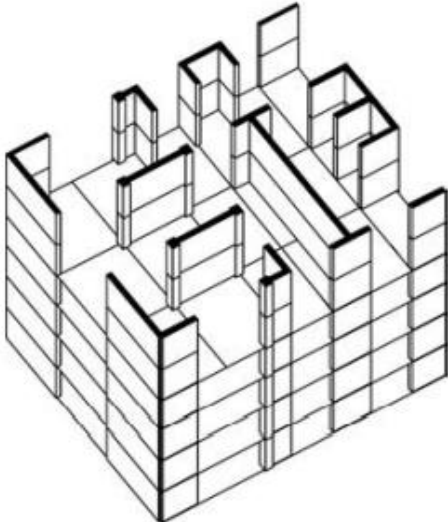
Figure 2- 3 Types of cantilever structural walls
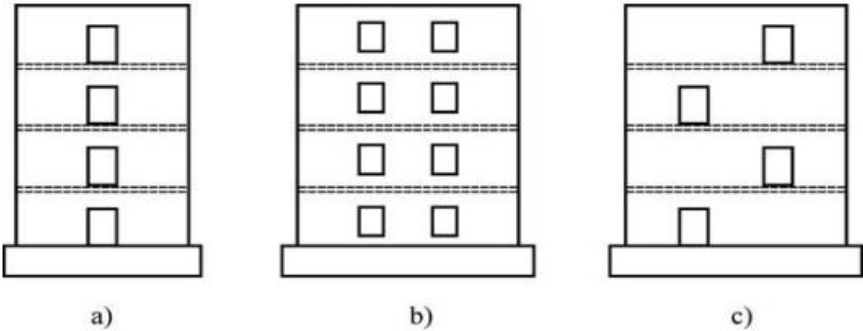
Figure 2- 4 a) Structural walls with openings, b) Coupled walls, c) Walls with staggered

Structural walls supported by columns at the first floor have been used in the past, in order to obtain architectural freedom (large rooms) at this level. These are walls with weak and soft story. They evidenced very poor seismic behavior and nowadays are abandoned.

2.2.3 RC Dual Systems:

Structures combining frames and shear walls as lateral resisting systems are called dual systems. Shear walls are the common vertical elements that are used to resist the lateral loads such as the seismic and wind load. These members take many forms according to their distribution in the buildings or to their functions like the core, the coupled, and the planar walls.

These vertical diaphragms are more suitable to use in low-rise to medium-rise constructions up to 20 floors. They are not the first choice for open spaced buildings or in the external glazed walls because of architectural functions. The shear walls offer good stability for buildings, limit the drift-story and increase the natural lateral frequencies of these buildings. The shear walls may be constructed together with frames to form shear wall-frame interaction system, and this system is one of the most popular systems in the world in resisting seismic loads in medium-to-high rise buildings. Not only does it offer the benefits of both systems together but also eliminate their mutual drawbacks. The interaction between the moment resisting frame and the shear wall is shown in Fig. 2-5, the frame basically deflects in a shear mode while the shear wall responds by bending as a cantilever at higher stories.[3]

Figure 2- 5 Shear wall-frame interaction
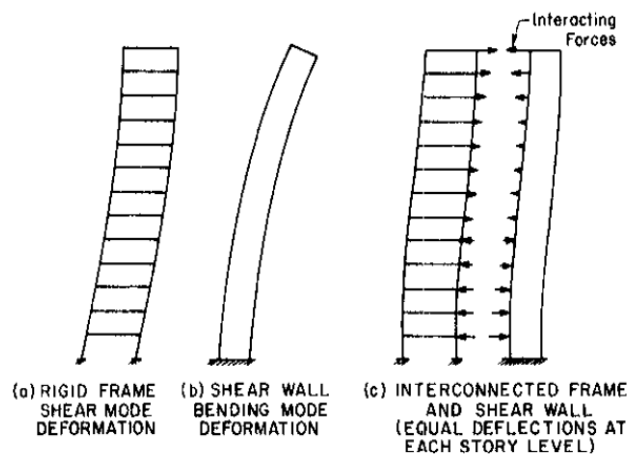
Figure 2- 6 Deformation modes [17]

Generally, for high-rise buildings, frames are placed around the perimeter of the building and shear walls are placed at the center of the structure around staircases or lifts.

However, if an increase of the torsional rigidity of the building is sought, designers tend to place shear walls at the perimeter of the structure.

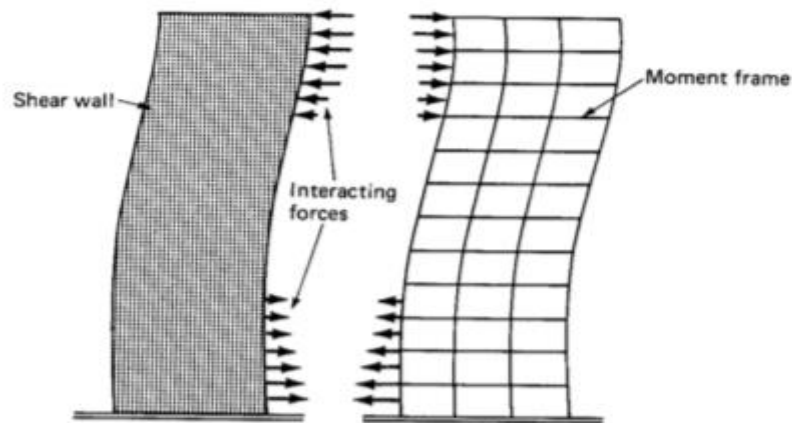The main advantage of the dual system is that it combines the stiffness of shear walls and the energy dissipation of the moment resisting frames. It has two lines of defense against earthquake effects the first one is the formation of plastic hinges at the base of the shear walls and the second one is the moment resisting frames that play its role after plastic hinges has been formed.

2.3   Code Definitions of RCDS:

Several countries from all around the world are using the dual systems as prime choice system to have a stronger line of defense against the earthquake effects. Definitions for this system are given in seismic codes such as the Algerian Earthquake Resistant Regulations «RPA 99»/Version 2003, the American standard building code and others.

RCDS is defined within the different codes as follows:

- **Eurocode 8:**

Dual system is a structural system in which support for the vertical loads is mainly provided by a spatial frame and resistance to lateral loads is contributed to in part by the frame system and in part by structural walls, coupled or uncoupled.[14]

- **American Society of Civil Engineers:**

Dual system is a system where the moment frames shall be capable of resisting at least 25 percent of the design seismic forces. The total seismic force resistance is to be provided by the combination of the moment frames and the shear walls or braced frames in proportion to their rigidities.

- **Algerian seismic code RPA99v2003:**

Dual system is a system where the shear walls carry less than 20 percent of vertical loads. The horizontal loads are jointly carried by the shear walls and the frames in accordance to their relative rigidities and the effects of the interaction between the shear walls and the frames must be considered. The frames shall have the capacity to resist not less than 25 percent of the story shear force in addition to the forces due to the vertical loads.[32]

2.4   Structural Constraints and Design Rules for Optimizing the RCDS:

To promote safety, reliability, and efficiency to our structural systems, we need to provide the right technical guidelines and structural constraints so that we eventually get the best and the most optimized systems.

According to the Algerian Earthquake Resistant Regulations RPA, when adopting the dual systems and in order to increase the effectiveness of our buildings against earthquakes, the first of the constraints is that we are obliged to design and place shear wall panels in a way where they would be able to carry roughly about 20% or a bit less of the vertical loads.

As known, structural optimization is an iterative process in nature. During the optimization process, structural analysis needs to be repeated many times to evaluate the improvement of each design until convergence is reached, which is an enormous computational task. Therefore, it is necessary to find a method to avoid repeating analyses for each iteration. For this purpose, an estimate of the gravity load that a shear wall may carry is very important to fulfil the 20% gravity load requirement. The following approach is adopted:[20]

For a given shear wall of length l_w, the covered area is defined as follows (Figure 2-7):

$$Tributary\ Area\ =\ (l_w\ +\ D)\ \times\ D \qquad\qquad \textbf{Eq. 1}$$

The distance D has been defined by trial and errors using the story height (*H*) and the shear wall thickness (*e*). For few trials, it has been found that *D = 11e* gives good results.
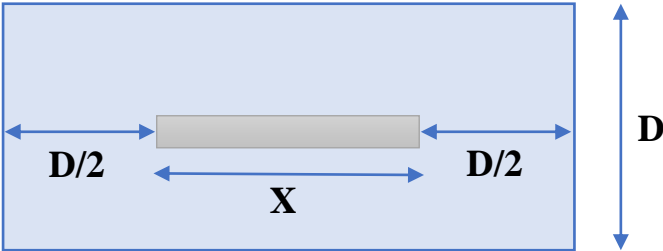
Figure 2- 7 The covered area

Similarly, the columns also ought to be designed and placed to be capable of resisting 25% of the story shear force in addition to the forces due to the vertical loads.

As for that, after finding the optimal positions for the columns, they must be designed to enable them resisting the gravity load coming from above using an approach that consists of:

- For each column (e.g., column **A**), the distances from both directions x and y in both sides to adjacent columns should be calculated.
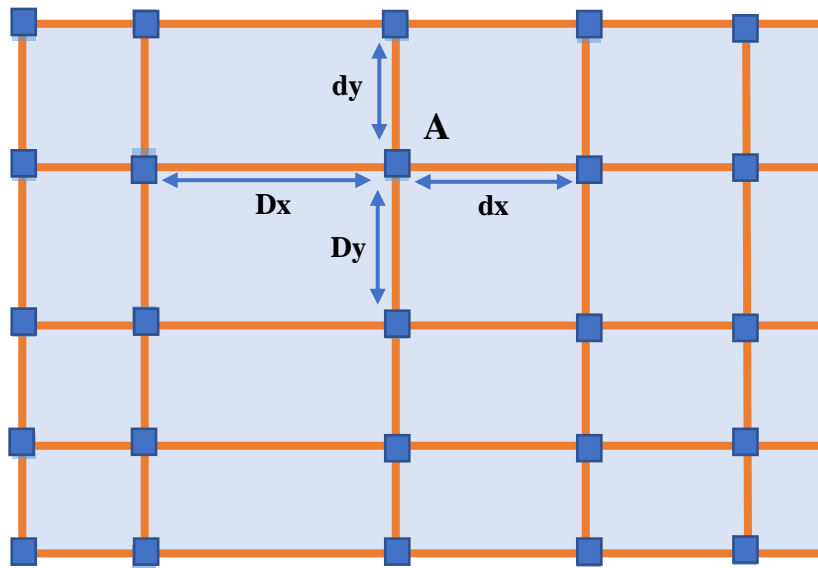
Figure 2- 8 Column adjacent distances

Where:

- Dx, Dy: is the max between the two distances in the x, y directions, respectively.

- dx, dy: is the min between the two distances in the x, y directions, respectively.

- Afterwards, we pre-design our column using the following table that provides the dimensions of that structural element in terms of the total height of the building and the maximum two distances, Dx and Dy.

Table 1 Column dimensions based on the span

L: length (m)		Total building height (m)				
Between 2 columns		3.00	6.00	9.00	12.00	15.00
3.00	4.50	0.30	0.35	0.40	0.45	0.50
4.50	6.00	0.45	0.50	0.55	0.60	0.65
6.00	7.50	0.60	0.65	0.70	0.75	0.80
7.50	9.00	0.75	0.80	0.85	0.90	0.95
9.00	10.50	0.90	0.95	1.00	1.05	1.10
10.50	12.00	1.05	1.10	1.15	1.20	1.25

Alike the shear walls, each column has also an area which it can carry, this latter was concluded after applying an iterative process, starting off from an idea of using beams and their tributary areas then ending up using uniquely columns separately. This iterative process led us to the next result: to find the covered area by a certain column, proceed by taking this column's both

dimensions and multiply them by 10. e.g., for a column, whose dimensions are 40 cm and 55 cm, its covered area is as follows:

$$Tributary\ Area\ =\ (55\ \times 10)\ \times\ (40\ \times 10) \qquad \textbf{Eq. 2}$$

the next figure illustrates that process:
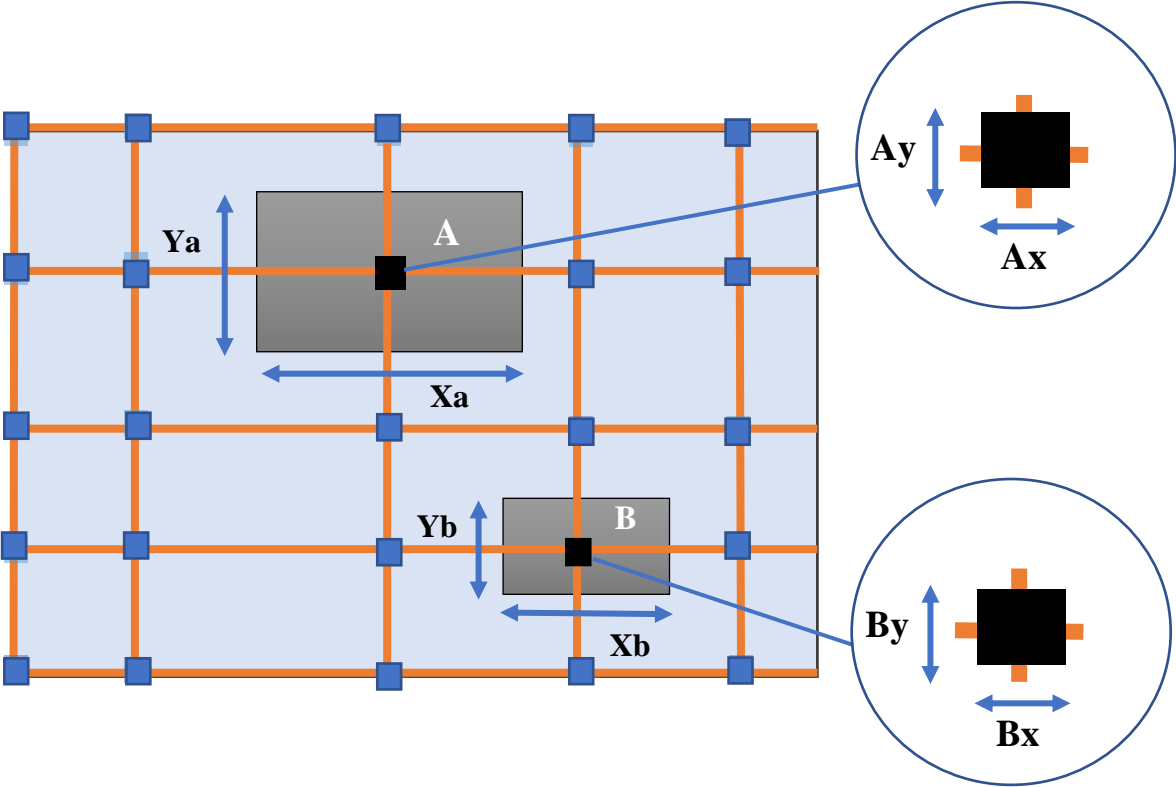
Figure 2- 9 Covered areas by columns

Where:

- Xa, Ya: are the covered area's dimensions for the column **A** in the directions x, y respectively.

- Xb, Yb: are the covered area's dimensions for the column **B** in the directions x, y respectively.

- Ax, Ay: are the column **A**'s dimensions in the directions x, y respectively.

- Bx, By: are the column **B**'s dimensions in the directions x, y respectively.

With:

- Column **A**'s covered area = Xa × Ya.

While:

$$Xa = 10 \times Ax$$

$$Ya = 10 \times Ay$$

- Column **B**'s covered area = Xb × Yb.

While:

$$Xb = 10 \times Bx$$

$$Yb = 10 \times By$$

(more details about the placement of these load bearing elements will be highlighted in the next chapter)

Furthermore, there must be a continuous load path, which can be achieved by avoiding any staggered vertical element from the top to the foundation. Fig 2-10 illustrates the unwanted irregularity in elevation.

Figure 2- 10 Unallowed Disruption of vertical load path [28]

With regards to the given structural constraints, some resulted layouts can be fairly satisfying but not as much optimized as possible. Therefore, an attempt to introduce some other parameters which can play a key role on improving these shortcomings is a must, these parameters can vary but some of them are mandatory in order to make sure these buildings are safe and strong, such parameters can be the: eccentricity, torsional radius.

Knowingly, the configuration of shear walls in plan of building will affect the seismic design of structure. The position of these walls along with the columns will change the stiffness of each floor in the structure, the diaphragm's center of mass displacement, and the drift of floor. Structural engineers preferred to arrange the shear walls in buildings in such a way that the center of stiffness is as close as possible to the center of mass, in each direction. So, under

the effect of the lateral load, the generated moment will not be enough to twist and damage the structure. [28]

The higher the eccentricity between the center of mass and stiffness, the worse is the distribution.

And to find the position of stiffness center, we carry out the next calculation:

$$x_S = \frac{\sum l_{yi}^3 x_i}{\sum l_{yi}^3} \quad \text{and} \quad y_S = \frac{\sum l_{xi}^3 y_i}{\sum l_{xi}^3} \qquad \textbf{Eq. 3}$$

Where:

- x_s and y_s are the coordinates of the center of stiffness.

- l_{xi} and l_{yi}: the length of a given shear wall i in the x and y directions, respectively.

- (x_i, y_i) are the coordinates of the center of the shear wall i relative to the stiffness center.

 Besides, the shear walls should be also positioned as far as possible from the floor center in order to maximize the torsional stiffness. This can be achieved by optimizing the torsional radius ratio $\dfrac{r_y}{l_s}$ in each direction. One of the conditions of regularity in plan and non-torsional flexibility of a structure is to have this ratio higher than unity. [28]

The expression of the torsional radius along the x direction of analysis is given by:

$$r_y^2 = \frac{\sum(x_i^2 l_{yi}^3 + y_i^2 l_{xi}^3)}{\sum l_{xi}^3} \qquad \textbf{Eq. 4}$$

where:

- y is the horizontal direction perpendicular to the direction x under consideration.

- (x_i, y_i) are the coordinates of the center of the shear wall i relative to the stiffness center.

- r_y: is the torsional radius of the shear walls of the considered floor.

- l_{xi} and l_{yi}: the length of a given shear wall i in the x and y directions, respectively.

- subscripts x_i and y_i vary from 1 to the total number of shear walls in x and y directions, respectively.

- l_s is the radius of gyration of the floor mass in plan.

The next figure depicts what is explained above and shows what is considered as a good and a poor shear walls' distribution.
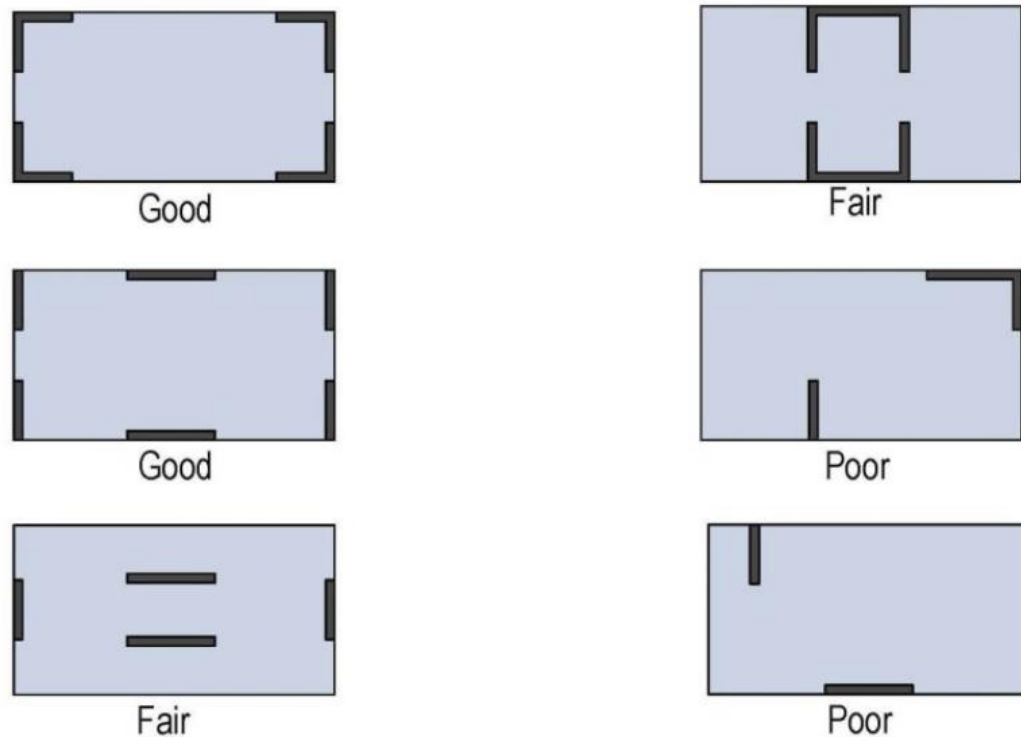
Figure 2- 11 shear wall distribution

2.5   Conclusion

Combining the advantages of both moment resisting frames and shear walls, the dual systems considerably extend the use of reinforced concrete for multistory buildings. The key of developing optimum solutions with dual systems is the harmonious working together of architect and structural engineer. Seeking for best building configuration which complies with functional, esthetics and structural requirements, finding appropriate location for structural walls within the building layout, correctly solving the loads transfer to the soil through well-conceived infrastructure are tasks of crucial importance for designers' team of high and super-high-rise buildings. Dual systems are in many cases the best solutions for tall buildings with various destinations.

Besides, the formulas chosen for the shear wall and the column's covered area appeared to be too essential, hence, an operation of several trials ought to be performed to opt for the best one which results in judicious outturn. Moreover, the placement of shear walls plays a pivotal role when considering a structure with a considerable torsional stiffness, in addition to the eccentricity.

Chapter 03: Automatic Determination of the Potential RCDS Elements Positions

3.1 Introduction

While designing buildings is the responsibility of the architect, civil engineers carry it a step further by defining the load bearing and supporting structures to ensure it satisfies the constraints implied by the regulations, which will lead to successfully carrying the loads, whether they are dead, earthquake or other types of loads. The main objective of this chapter is to implement the conventional engineering way of thinking into an algorithm that determines the possible positions of the frames and shear walls.

For an engineer, placing the columns for example can be spontaneous based on the information provided by the architectural layout and by using the knowledge previously gained. In our program, the architectural layout is seen as a set of polygons for walls or voids for openings such as doors or windows. On the basis of a set of rules and criteria, the algorithm defines all the potential positions that can be used for the RCDS elements.

An important note about this chapter is that, at this stage, the program gathers all possible positions of the frames and limits the walls to only those that can contain shear walls to be used later and does not necessarily find the best solution. This step serves the optimization by limiting the search space and design variables which are key components of any optimization problem in addition to the objective functions and constraints that are discussed in the fourth chapter.

3.2 Converting Architectural Layout into Processible Data

3.2.1 IFC File

IFC is short for International Foundation Class, files using the IFC file format are Building Information Modelling (BIM) files. However, unlike other BIM file formats, IFC files are platform neutral and can be read and edited by any BIM software. The idea behind IFC is to enable interoperability between BIM software and boost collaboration within the Architecture, Engineering, and Construction (AEC) industry [31]. With Revit, exporting the IFC file of an architectural layout is simple, and objects are automatically assigned to their types and classes (Figure 3- 1).

3.2.1.1 IFC Classes and Types

An IFC entity is a uniquely defined object in the IFC data model. Depending on the entity assignment and type definition, the object is allocated certain default attributes and dependencies within the IFC schema. Choosing the right entity is crucial when exporting IFCs: if a wall is not assigned to the entity IfcWall, it is not allocated all the attributes that it requires to be described clearly. This means that it is not interpreted correctly by other coordination or evaluation programs in turn [5].
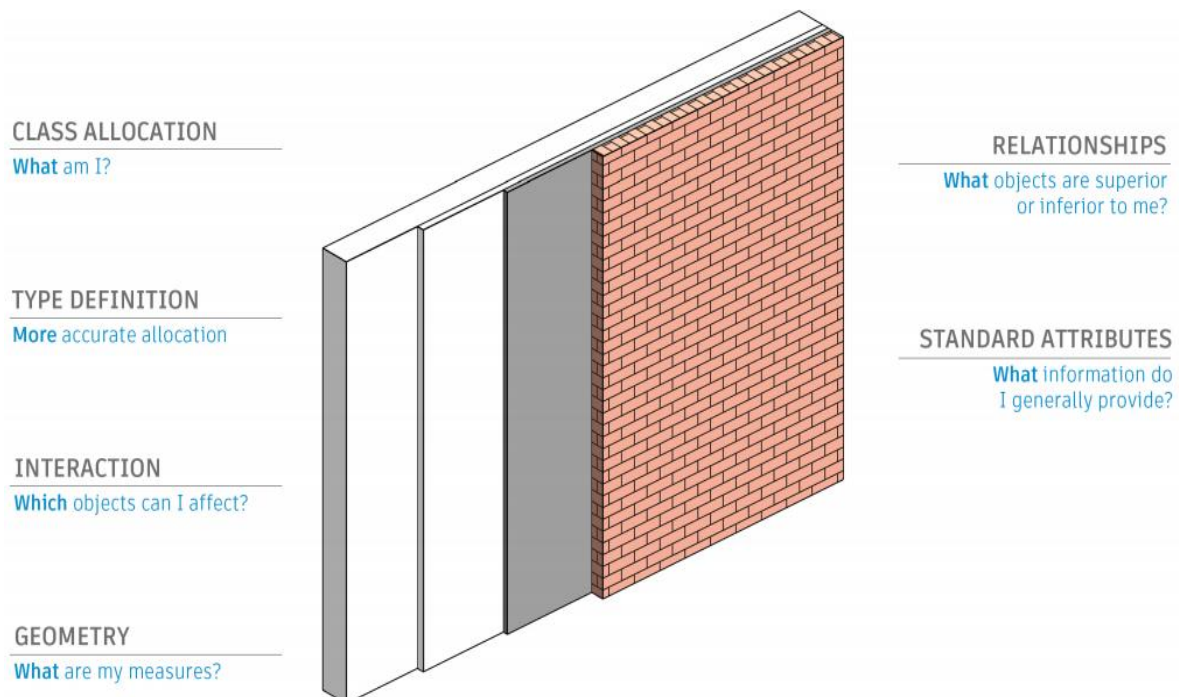
Figure 3- 1 Classes and types of IFC objects [5]

Distinctions are not only made between major categories, so components can also be assigned as entities to reproduce them more accurately within the IFC data model. This classification can roughly be compared to the sub-categories in Revit (Figure 3- 2).

In our program we needed to import objects of classes: walls, slabs/floors, openings (windows, doors), the interaction between them, their geometric measures and positions in a 3D coordinate.

Examples:

ifcWall:

```
#9211= IFCWALLSTANDARDCASE('1CsCG5NTvEAQSOxgbnIifs',#41,'Wand-Int-ERDG-
2',$,'Basic Wall:G\X2\00E9\X0\n\X2\00E9\X0\rique - 200 mm -
Plein',#9191,#9209,'147666');
```

ifcOpenElement:

```
#10706= IFCOPENINGELEMENT('1CsCG5NTvEAQSOxhfnIifr',#41,'Wand-Int-ERDG-
3',$,'Opening',#10705,#10700,'147663');
```

ifcSlab:

```
#8352= IFCSLAB('2IuD6UufP6YgRoFmwdoClQ',#41,'Floor:B\X2\00E9\X0\ton sur
place 225\X2\00A0\X0\mm:139507',$,'Floor:B\X2\00E9\X0\ton sur place
225\X2\00A0\X0\mm',#8330,#8350,'139507',.FLOOR.);
```
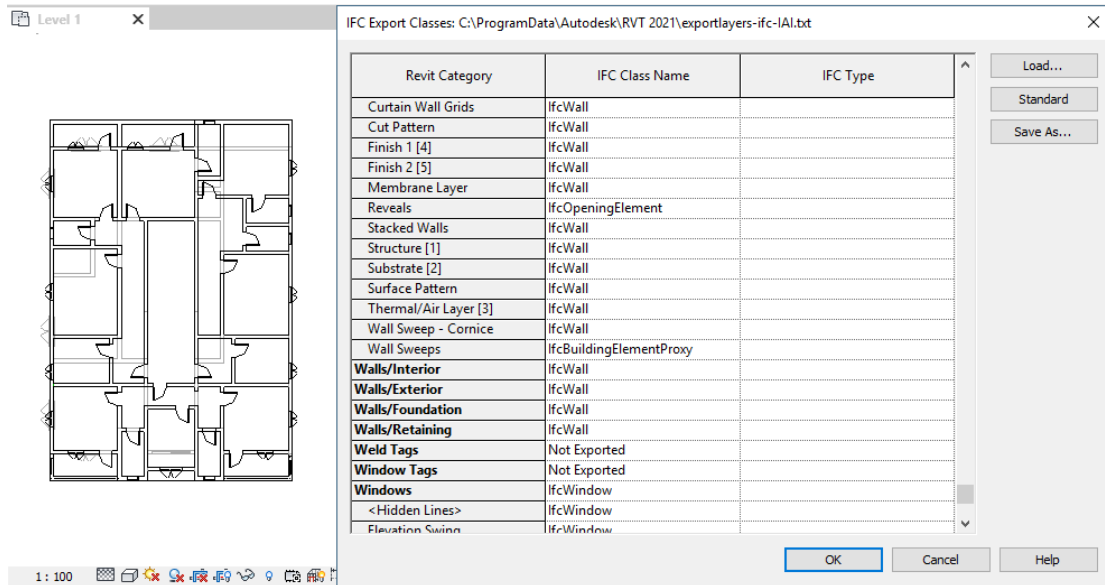
Figure 3- 2 Revit IFC exporting options.

3.2.1.2 Reading the IFC File and Plotting the Layout

In order to use the data after exporting the architectural layout, it is convenient to use a library like IfcOpenShell, which is an open-source software library that helps users and software developers to work with the IFC file format using either C++ or Python as in this project.

All walls, slabs and open elements of each floor are then imported from the IFC file to separate lists by the commands that the library IfcOpenShell provides and by using the class name as in this example:

```python
import ifcopenshell as ifc
f = ifc.open(fileName)
# Get a list of all walls in the file
walls = f.by_type("IfcWall")
```

The walls are then transformed to simpler in plan geometric objects, openings to discontinuities in the walls and the slab to an area covering all these elements.

Passing by the step of transforming elements of the layout into simpler geometric objects identified by their dimensions and coordinates is essential for the following step of extracting the axes and placing the columns. Furthermore, visualizing any progress achieved during the work is critical and is made possible thanks to this transformation as clarified in Figure 3-3.
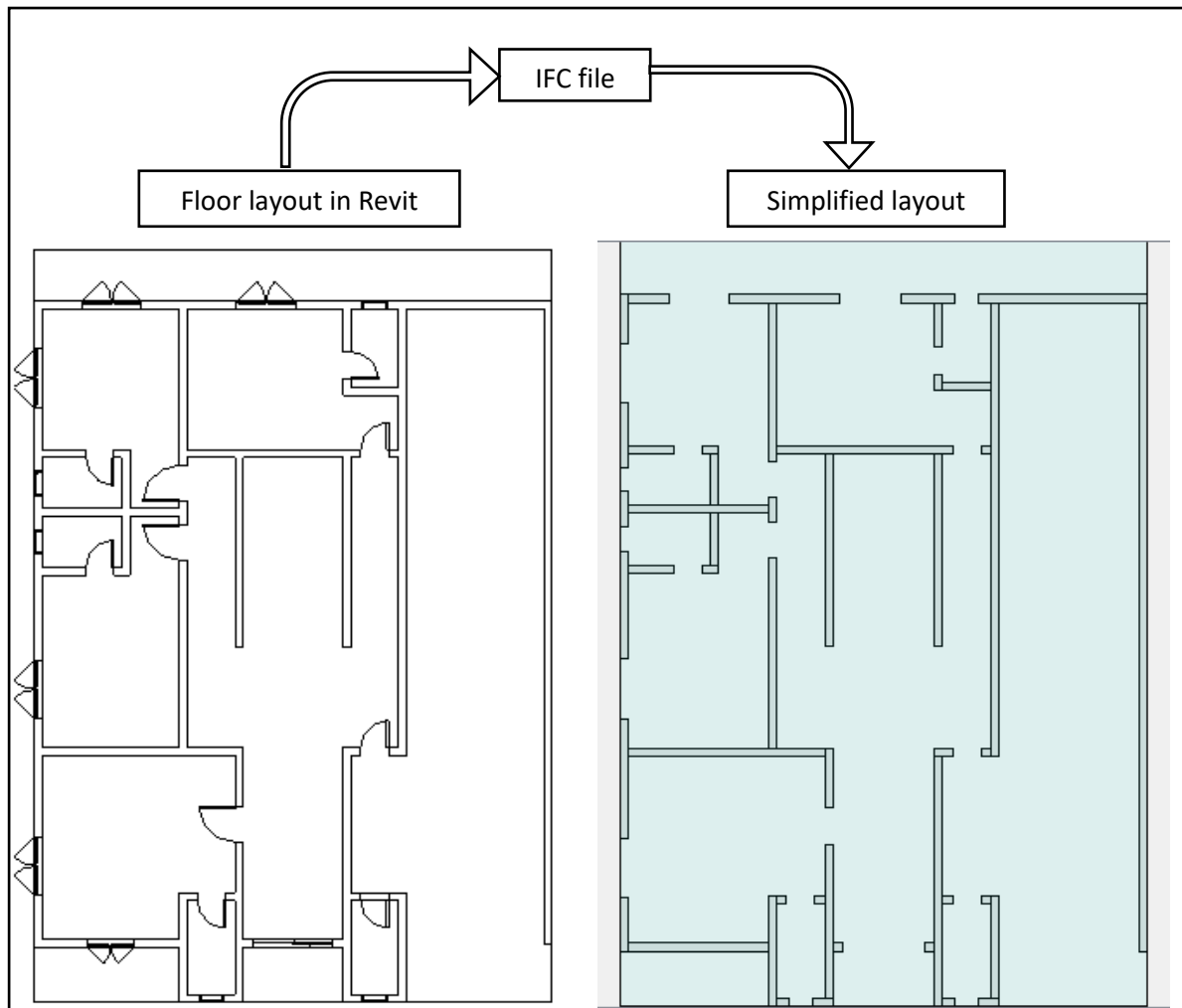
Figure 3- 3 Revit IFC exporting options.

3.2.2 Determination of the Potential Frames

A concrete frame is a common form of structure, comprising a network of columns and connecting beams that forms the structural 'skeleton' of a building. This grid of beams and columns is typically constructed on a concrete foundation and is used to support the building's floors, roof, walls and so on [12].

For the algorithm to generate an optimized grid of frames for any given layout that both respects the architectural shape and the structural regulations, there need to be first a way to determine all the possible positions that can be considered for a column. It is preferable but not required that a column is at the intersection point of two walls, or more specifically the intersection point of two wall axes that belongs to a wall and is under the slab surface.

3.2.2.1 Problems Faced with this Approach

If we consider each column separately, generating an acceptable frame system will be laborious and presents various problems as shown in Figure 3- 4.

1. Short distance between two columns, therefore, the beam is endangered by the high shear effect of the lateral load.
2. Long distance between two columns which makes the beam under the risk of a lateral deflection.
3. Intersection of two beams without the presence of a column
4. Non-aligned distribution of columns which results in inclined beams
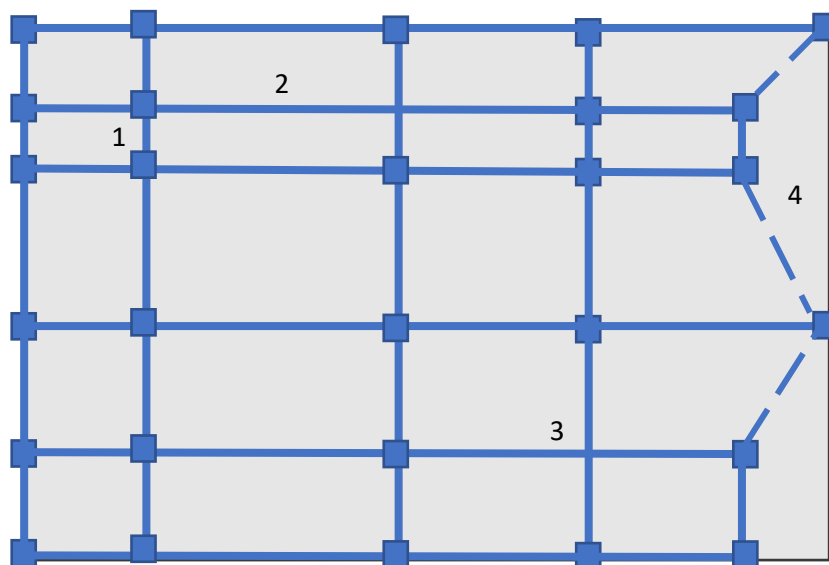
Figure 3- 4 Axes and potential column with undesirable cases

3.2.2.2 The enhanced approach

Instead of working on separate columns that may not be aligned – problems such as beam placement might occur – an approach that relies on the walls' axes is considered. A given axis will contain several columns which are the intersections with other axes as shown in the example Figure 3-5.

From this collection of axes and intersections a grid can be selected by avoiding cases shown in in Figure 3-5 using the Tabu Search method explained in the next chapter:

Cases to avoid:

1. Column that is not contained by a wall: it is preferable to only select column positions that belong to the architectural layout in order to not interrupt either a useful area (column in the middle of the room) or where openings in the wall are present (windows or doors) (Figure 3-5.1)
2. Short span: for a practical grid, two adjacent axes should have a minimum span to respect (2.5 meters) (Figure 3-5.2)

3. Avoiding wide cantilevers: As long as this respects the two previous points, choosing an axis at the edge is preferable to avoid having a cantilever (Figure 3-5.3)
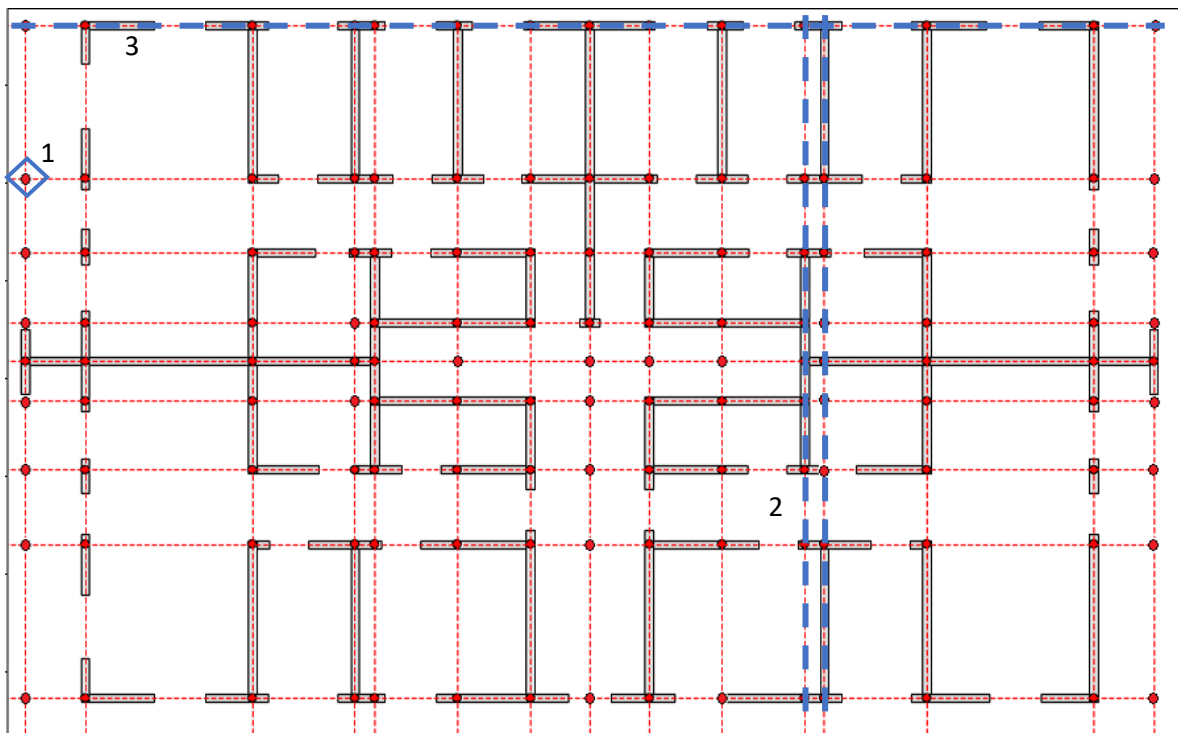
Figure 3- 5 Axes and potential column with undesirable cases

3.2.3 Shear walls placement

After generating the frames grid, the possible positions of the shear walls should be limited to the walls included in the grid. In addition, a distance specified by the engineer should be respected between two load-bearing elements (shear wall-shear wall or shear wall-column) to avoid having short beams as clarified in the Fig 3- 6.
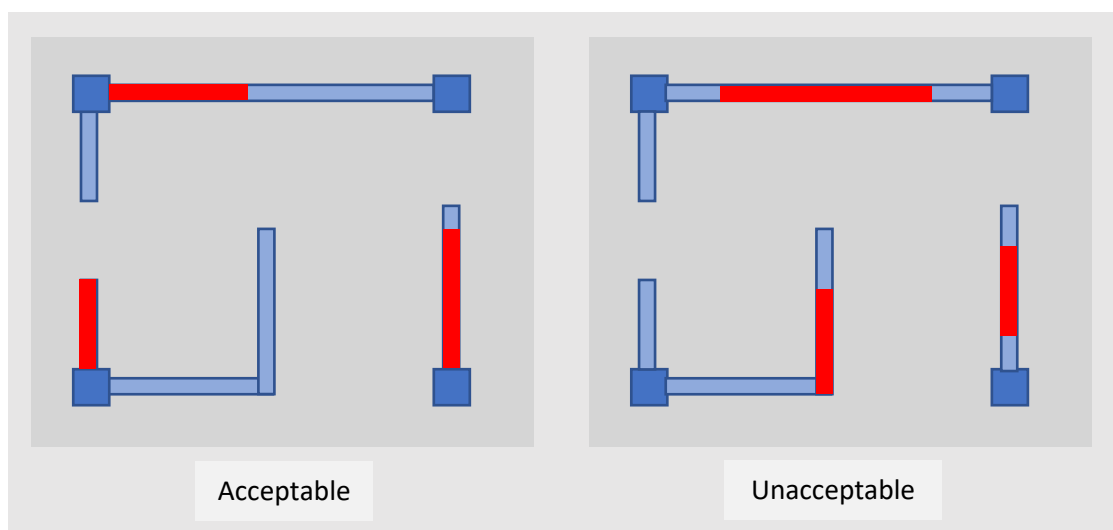
Figure 3- 6 Shear walls placement

3.3 Conclusion

Data provided by the IFC file of any building's architectural layout is valuable yet not directly employable in our case with its raw format. The work done in this chapter can be summarized into two essential points:

Transforming this data to a simpler format of geometric shapes. Therefore, it was possible to gather any needed information such as walls' axes, openings positions and slab shape in addition to their criteria that are ready and simple to manipulate.

The second point consists of finding a practical approach to follow in terms of generating the frames. The solution adopted was by using the axes with the previously mentioned cases to avoid. Fixing this allowed us to limit the data even further to what is needed for the Tabu Search algorithm.

To conclude, the work done in this chapter consists of providing the indispensable components for the optimization problem which are the search space and design variables.

Chapter 04: Automatic Generation and Optimization of RCDS Design

4.1 Introduction

With the advent of computers, and as part of the Construction 4.0 concept, optimization has become a part of computer-aided design activities. With the presence of a large number of optimization algorithms, for a given optimization problem, the choice needs to be made based on the type of the problem, available data and constraints.

According to what is previously elaborated, since the two problems (frames generation and shear walls placement) required separate reasoning and processing, we concluded that the use of a combination between two convenient approaches, Tabu Search for the frames generation and a Genetic Algorithm for the shear walls is what resulted in being practical.

The current chapter consists of the abovementioned two main sections serving the optimization purpose. First, adapting the data at hand to the tabu search. The result is then exploited by the genetic algorithm with the needed changes, to finally reach the wished objective.

4.2 Optimization

Optimization refers to acquiring the best outcome under specific conditions. In the field of civil engineering, optimization can be executed in each step of a project life cycle such as design, construction, operation, and maintenance. One of the most commonly used types of optimization is structural optimization, which refers to an optimization to find the best structural components to achieve certain objectives under prescribed conditions. Structural optimization can be divided into the following four categories:

1. Size optimization: also known as sizing optimization, which treats the cross-sectional areas of structures or structural members as the design variables.

2. Shape optimization: also known as configuration optimization, which treats the nodal coordinates of structures as the design variables.

3. Topology optimization: focuses on how nodes or joints are connected and supported, aiming to delete unnecessary structural members to achieve the optimal design.

4. Multi-objective optimization: simultaneously considers two or more of the above optimization objectives for better optimization results; an optimization involving size, shape, and topology at the same time is also known as layout optimization.

At the early stage, research on structural optimization in the field of civil engineering only involves mathematical theorems and programming techniques based on simple structures as benchmarks. With the development of computational and construction techniques, structural optimization has become increasing popular and has been applied to larger and more complex civil engineering structures, especially topology optimization. One of the principal objectives of structural optimization is minimizing the total cost of the structure. In construction projects, a lower cost is always desired on the premise of satisfying the requirements of structural performance. Many studies have been reported to reduce the total cost by minimizing the total weight of the structure. In addition, some research articles on structural optimization focus on

improving certain structural performance such as mechanical behavior, aerodynamic performance, and dynamic seismic performance in order to adapt the structures to different environments.

To achieve the above-mentioned objectives, many optimization methods have been proposed and developed. Recently, metaheuristic methods have become one of the most popular optimization methods in civil engineering structural optimization research because they are suitable for combinatorial optimization problems. These above-mentioned studies in the field of structural optimization presented the achievements and potential of structural optimization to improve the efficiency and sustainability of the civil engineering industry. The two concerned algorithms are combined in one program while the second takes the result of the first as an input to carry on the optimization.

In the civil engineering industry, there is always a common criterion to evaluate a project, which is minimizing the cost while maximizing safety through several criteria such as symmetry, torsional radius, covered area…etc. However, these goals may conflict with each other, which means that improving one of them implies worsening another one. Therefore, increasing studies have focused on balancing the competing objectives in the field of structural optimization. This type of structural optimization is usually termed as multi-objective optimization, which is defined as the last type of structural optimization objective. One of the major differences between multi-objective optimization and the single-objective optimization is that more than one objective function is considered in multi-objective optimization. For example, researchers may consider minimizing weight and deflection simultaneously. Obviously, multi-objective optimization problems are more complex and require more advanced computational methods. Another major difference is that there is not a unique solution that reaches the optimum of all objectives simultaneously, which is determined by the intrinsic feature of multi-objective optimization. Generally, a multi-objective optimization problem can be formulated as Equation:

Minimize the vector function: $f(X) = [f_1(X), f_2(X), f_3(X) \dots \dots \dots f_k(X)]^T$

Subject to: $\qquad\qquad\qquad g_1(X) \geq 0, i = 1,2,3, \dots \dots m,$ **Eq.5**

$$h_j(X) = 0, \qquad j = 1,2,3 \dots \dots p, \qquad X \in S$$

where $f(X)$ is the set of objective functions; $g_i(X)$ and $h_j(X)$ refer to the inequality and equality constraints; $X = [x_1, x_2, x_3, \dots \dots, x_n]$ is the set of design variables; and S is the search space of the solution. As mentioned above, no unique optimal solution can be obtained from the formulation, and the optimization result consists of a series of trade-off solutions in fact. These solutions are known as no-dominated solutions and the set of these solutions is known as Pareto optimal set. The Pareto optimal set, when it is plotted in the coordinate system considering the design criteria, is referred to as the Pareto front, which is a useful tool to display the result of multi-objective optimization. It is convenient for the designer to make trade-off decisions between the competing objectives. The constraints for multi-objective optimization is a combination of the constraints for each objective [20].

4.3 Tabu Search

The Tabu Search algorithm was developed independently by Glover [1986] and Hansen [1986] for solving combinatorial optimization problems [10]. Similarly, to most meta-heuristics it is an improving iterative procedure that moves from a given solution to a solution in its neighborhood that is better in terms of the objective function value (or some other measure based on the solution characteristics). Thus, at each iteration, a local search procedure (the "original" heuristic) identifies and evaluates solutions in the neighborhood of the current solution, selects the best one relative to given criteria, and implements the transformations required to establish the selected solution as the current one. Inferior quality solutions encountered during neighborhood explorations may be accepted as a strategy to move away from local optima. In theory, the procedure iterates until no further improvement is possible. In actual implementations, a more restrictive stopping criteria is used: total number of iterations, relative improvement over a number of iterations, etc (Figure 4- 1).
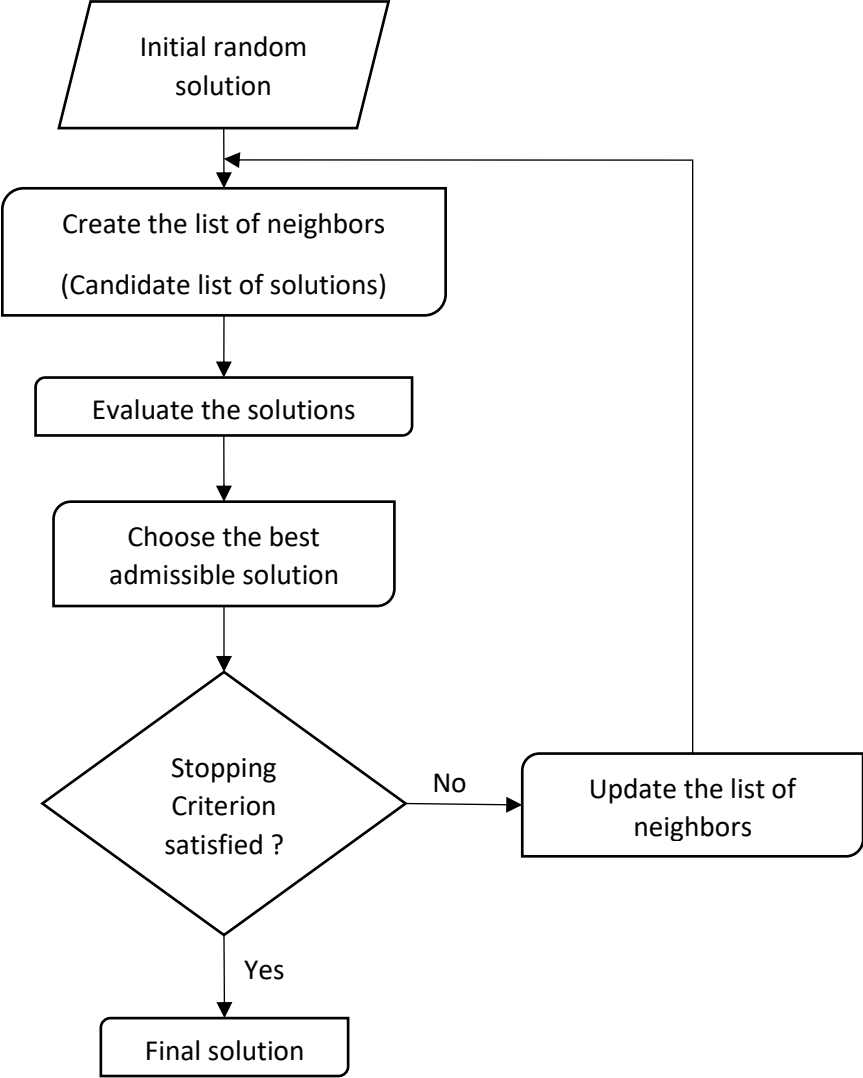

Figure 4- 1 Flowchart of the Tabu Seach algorithm

4.3.1 Procedure of Generating an Optimal Frame Grid Using Tabu Search

The procedure adopted to generate an optimal frame grid capable of resisting gravity and lateral load is composed of the following steps:

Axes' positioning:

1. Number of spans: in a specific direction, the number of axes depends on the dimension of the slab. An optimum or target span can be set. In this instance the goal span is set to 4 meters, therefore, the following formula is used to determine the preferred number of columns for a given Lx or Ly, the slab dimensions in the x and y directions respectively:

$$n_x = \frac{Lx}{4} + 1 \qquad \text{Eq. 6}$$

Where N_x the preferred number of axes is equal to n_x rounded to the nearest whole number.

In the example of Figure 4- 2, supposing the three unwanted cases are avoided, with $Lx = 17.5\ m$, we will have $N_x = 5$ which translates to approaching a grid with four spans in the x direction.
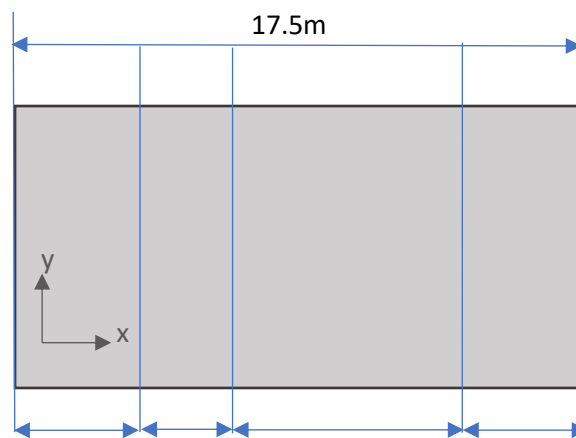

Figure 4- 2 Number of spans to slab dimension

2. Spans with the same length: having equidistant axes does not only help in achieving the symmetry but also in generating columns with the same dimensions, which is practical during the construction step.
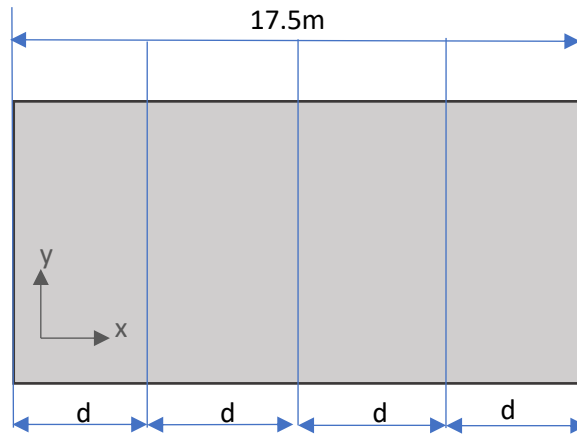
Figure 4- 3 Example of equidistant axes

Achieving the equidistance in addition to the preferable number of spans guarantees having beams with reasonable depths and avoids short elements.

4.3.1.1 Generating the initial random solution

As a first step, a random first solution, which consists of a set of vertical and horizontal axes forming a grid, is generated. However, initializing with a slightly approached proposition through some constraints will kick start the algorithm in the right direction which reduces the total number of iterations needed, in the following Figure 4- 4 an example of a random first solution is illustrated:

Selected axis	Non selected axis

Intersection of selected axes with the possibility of a column

Intersection of selected axes without the possibility of a column

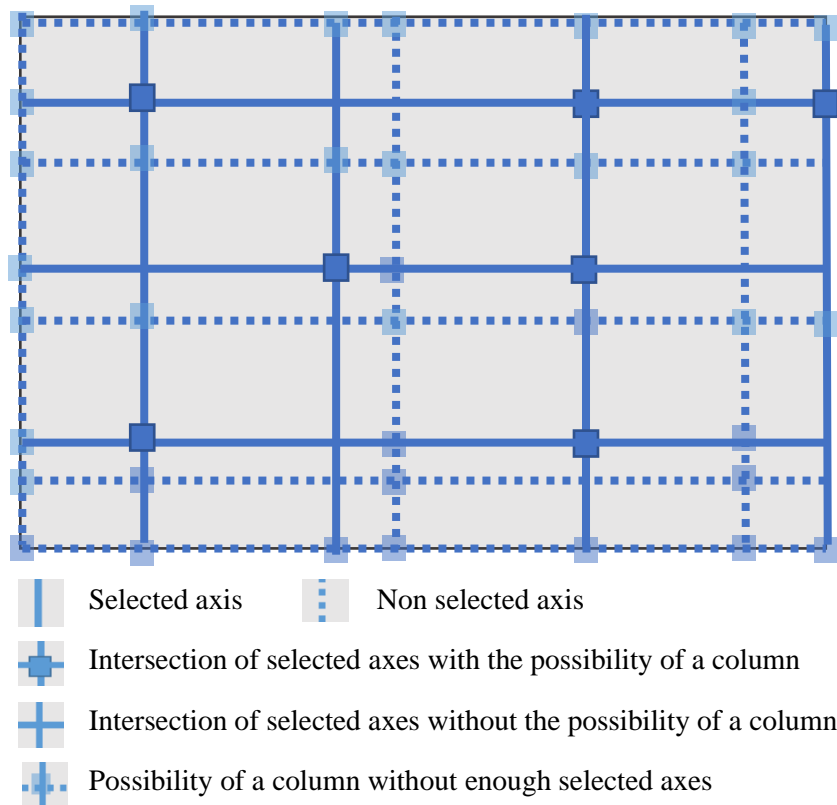Possibility of a column without enough selected axes

Figure 4- 4 Axes and potential columns with undesirable cases

The random first solution respects the condition of the minimum distance between two axes which is set to 2.5 meters and a maximum distance that does not exceed 6.0 m. These conditions are considered as constraints. The other non-satisfied conditions such as having beam intersections at a point with no possible column and the presence of cantilevers with unaccepted dimensions will be addressed in next steps.

4.3.1.2 Creating the neighbors' list

This step consists of performing a single simple change of either removing an axis, adding an axis. The combination of these two actions after two iterations or more can affect a moving operation of an axis.

In each iteration, all possible operations of removing and adding are executed on the considered configuration.

As illustrated in Figure 4- 5, Neighbor – 1 and Neighbor – 2 represent neighbors that resulted from adding a distinct axis, either vertical or horizontal. Whereas Neighbor – 3 came from removing an horizontal axis. Since all possible operations need to be executed, the neighbors' list will end up in an abundance of neighbors among which a better solution may come out.
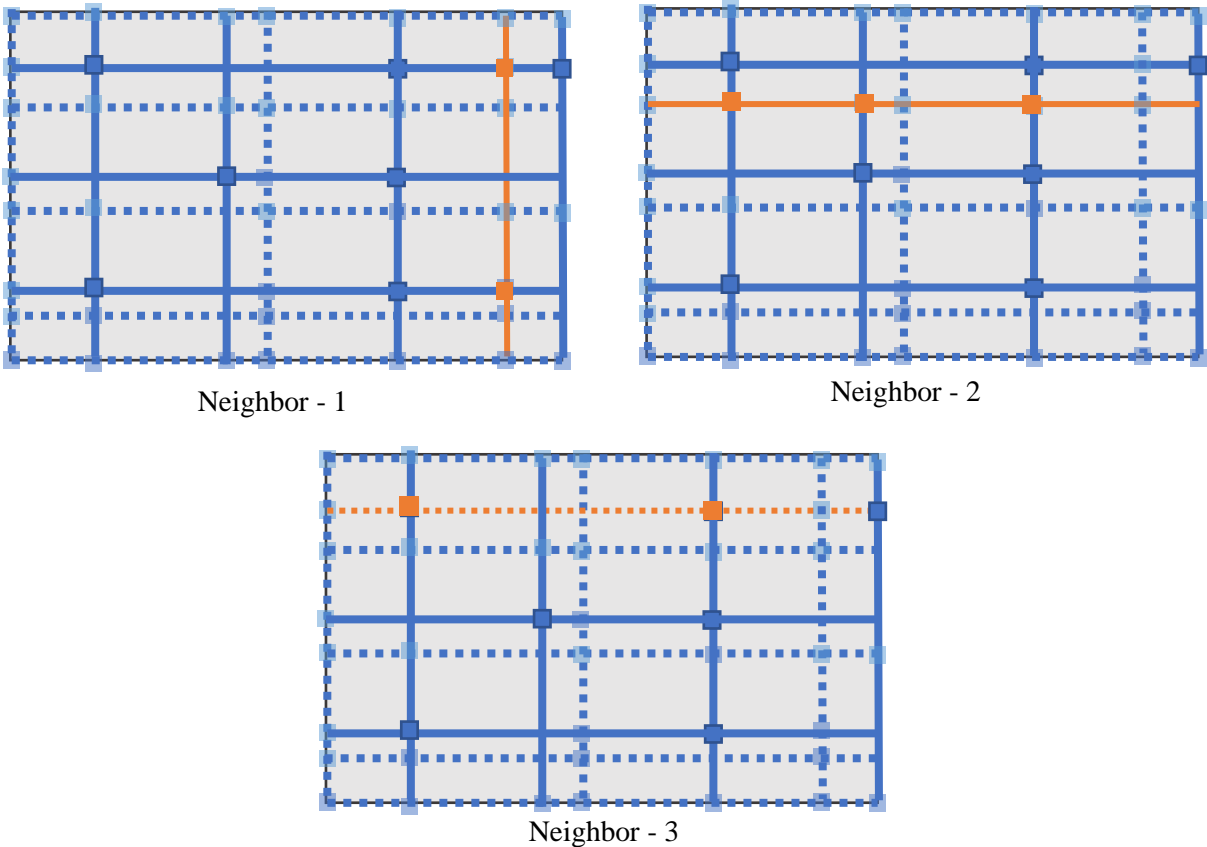

Neighbor - 1

Neighbor - 2

Neighbor - 3

Figure 4- 5 Samples from neighbors

4.3.1.3   Solutions evaluation

The evaluation of all the individuals in the neighbors list is crucial, therefore, a fitness function is needed. The fitness value is a numerical value that expresses the performance of an individual with regard to the current optimum so that different individuals can be compared. Usually, a spread of solutions exists ranging in fitness from very poor to good. The notion of fitness is fundamental to the application of evolutionary algorithms; the degree of success in their application may depend critically on the definition of a fitness that changes neither too rapidly nor too slowly with the design parameters of the optimization problem. The fitness function must guarantee that individuals can be differentiated according to their suitability for solving the optimization problem [1].

For any given neighbor these scores are calculated, taking in consideration their interval of variation that needs to be limited between 0 and 1, where 0 describes a perfect score in the situation.

- **Optimal number of axes:** In a given direction, the preferred number of axes (or spans between these axes) is calculated from the slab dimensions and a score formula is used to push the optimization towards having that number of axes:

$$Sn_x = \frac{|M_x - N_x|}{MaxError_x} \qquad \qquad \textbf{Eq. 7}$$

Where:
- In the previous chapter, calculating N_x is introduced as the preferred number of axes in the x direction.
- M_x is the axes' number of the considered solution.
- $MaxError_x = \max (T_x axes - N_x , \ N_x - 2)$ is the maximum error any proposed solution might have.
- $T_x axes$ is the total number of possible axes in the x direction, which means N_x represents a sample from $T_x axes$.

The value of S_x varies from 1 for the worst case to 0 for a perfect number of axes. Total score is then normalized as:

$$Score_1 = \frac{Sn_x + Sn_y}{2} \qquad \qquad \textbf{Eq. 8}$$

- **Minimum distance from the edge of the slab**: To avoid having cantilevers of important dimensions, the optimization is directed towards avoiding cantilevers or at least having only those of a limited width.

$$Se_x = \frac{D_{ex} + d_{ex}}{0.5 \ L_x} \qquad \qquad \textbf{Eq. 9}$$

Where :
- D_{ex} and d_{ex} are the distances from the closest axis from the edge to it in both sides respectively as portrayed in Figure 4- 6.

- L_x slab dimension in the x direction.

$$Score_2 = \frac{Se_x + Se_y}{4}$$

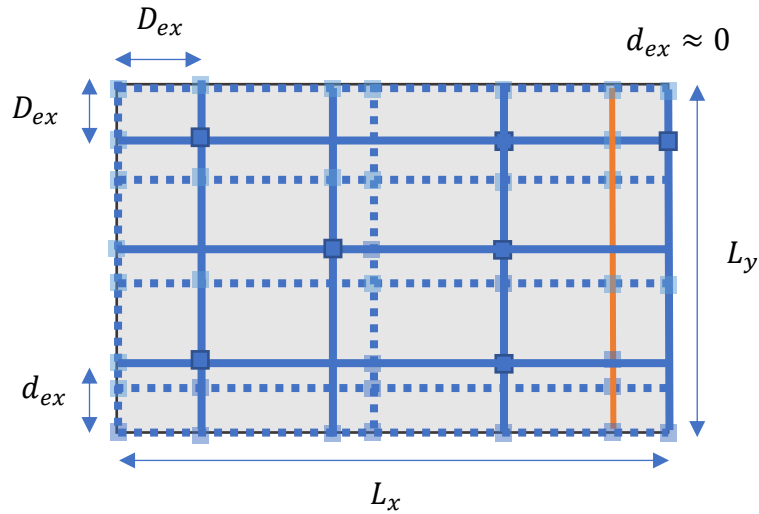<div align="right">Eq. 10</div>

Figure 4- 6 Edge score variables

- **Acceptable column positioning:** The intersection of the axes can truly be considered as a column only if this intersection is contained by a wall and is under the surface of the slab.

  Evaluating solutions based on the number of unacceptable number of columns' position is achieved by the formula:

$$Score_3 = \frac{I_V}{I_t}$$

<div align="right">Eq. 11</div>

Where:

- I_V: is the number of axes' intersections in a void (not contained by a wall and/or not under the slab surface)
- I_t: is the total number of intersections.

A solution with all intersections are accepted as column positions will have its $Score3$ equal to 0.

- **Equidistance:** In order to serve the symmetry of the configuration as well as having columns with the same dimensions that facilitates the construction phase, it is preferable to have equal spans. Hence, approaching a solution with equidistant axes is achieved by this score, where 0 is considered its best result:

$$S_{dx} = \sqrt{\frac{\sum(x_i - \bar{x})^2}{n-1}}$$

<div align="right">Eq. 12</div>

Where:
- x_i: span dimension in the x direction, $i = 0,1,2$ ....total number of spans.
- $\bar{x}$: is the target span dimension, $\bar{x} = \dfrac{L_x}{n_x}$

$$Score_4 = \frac{S_{dx} + S_{dy}}{2}$$ **Eq. 13**

4.3.1.4 Selection

At this stage, every configuration from the neighbors list is given a fitness value. The best is selected to be the starting point of the next iteration from which more neighbors are generated and so on. By trial and error, the weights and the combination that leads to fast convergence is concluded as:

$$Fitness = \frac{1}{1 + \sum w_i Score_i} \qquad i = 1,2 \ldots total\ number\ of\ scores$$ **Eq. 14**

w_i represent the weights associated with each score such as:

$$w_1 = 1,\ w_2 = 1,\ w_2 = 3,\ w_2 = 0.5$$

4.3.1.5 Termination

The stopping criterion represents the limit that the algorithm's loop will not exceed. In our case, and since the step of the neighbors' generation finds all possible changes to a certain configuration, a limit of 10 to 15 iterations gave satisfactory results. This proves the high convergence of the adopted approach.

4.3.2 Final solution

As for the example given, the solution will converge to the grid illustrated in the Figure 4-7. It is clear that all intersections do represent actual column positions. Span dimensions are acceptable, and any trial to change one of them will conflict with either the column existence at the intersections or avoiding cantilevers conditions.

The presence of one cantilever at the right edge is inevitable due to the other conditions that are given equal to higher importance through their weights.
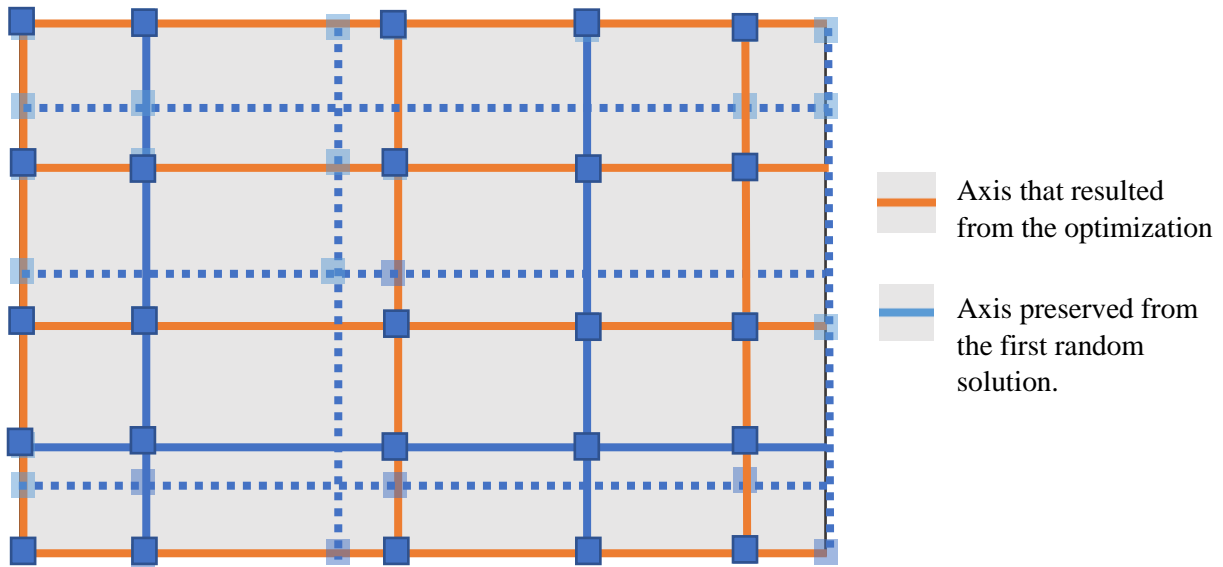
Figure 4- 7 Optimal solution

4.4 Genetic Algorithm

Genetic Algorithms are the translation of the biological concept of evolution into algorithmic recipes. They belong to the area of computer science related to machines and computer programs. As they are part of many intelligent systems, Genetic Algorithms are frequently counted to the areas of computational intelligence and artificial intelligence, which aim at constructing methods that imitate and even overcome human intelligence [4]. Meanwhile, a huge collection of methods has been proposed that fall into these categories. We will introduce the foundations of Genetic Algorithms. Starting with an introduction to the basic Genetic Algorithm with populations, we will introduce the most important genetic operators step by step, which are crossover, mutation, and selection [27].
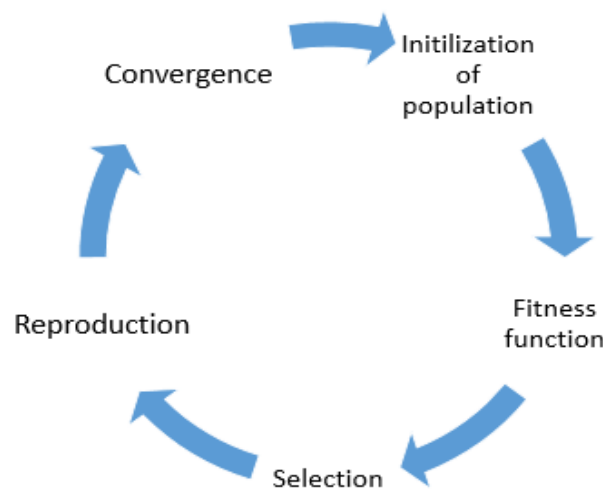

Figure 4- 8 Genetic Algorithm cycle

68

Definitions:

- **Population:**

In a GA, each iteration, or generation, results in a series of possible hypotheses for best approximating a function, and the population refers to the complete set or pool of these generated hypotheses after a given iteration [22].

- **Chromosome:**

In an obvious nod to biology, a chromosome is a single hypothesis of which many make up a population [22].

- **Gene:**

In a GA, potential hypotheses are made up of chromosomes, which are, in turn, made up of genes. Practically, in a GA, chromosomes are generally represented as binary strings, a series of 1s and 0s, which denote inclusion or exclusion of particular items represented by position in the string. A gene is a single bit within such a chromosome. [22]

- **Generation:**

In GAs, new sets of hypotheses are formed from previous sets of hypotheses, either by selecting some full chromosome (generally of high fitness) to move forward to a new generation unscathed (selection), by flipping a bit of an existing full chromosome and moving it forward to a new generation (mutation), or, most commonly, by breeding child chromosomes for the new generation by using an existing set's genes as parents. A generation, then, is simply the full set of the results of a GA iteration [22].

- **Evaluation of the solution:**

Much like the Tabu Search algorithm, to evaluate a solution, there are two things to consider:
- constraints: these are some conditions that must be met. That is a solution is rejected if it does not meet these constraints.
- fitness function: which is the target function of optimization. In the case of multi-objective optimization process, weights (scaling factors that are multiplied by the function value) are associated to each one of these values corresponding to their importance [4].

4.4.1 Generating the optimal SW distribution using the GA

Both shear walls and frames participate in resisting the lateral loads resulting from earthquakes or wind or storms, and the portion of the forces resisted by each one depends on its rigidity, modulus of elasticity and its ductility, and the possibility to develop plastic hinges in its parts. The moment-resisting frame must be capable of resisting at least 25 percent of the base shear, and the two systems must be designed to resist the total lateral load in proportion to their relative rigidities. As for the vertical load, shear walls need to be placed and designed to not exceed carrying 20 percent of vertical loads [31].

In order to adhere to the Algerian Earthquake Resistant Regulations for the RCDS with justification of frame-wall interaction, the GA is customized as follows:

4.4.1.1   Genetic Algorithm workflow

Given the edited architectural layout represented by the slabs, frames and only the architectural partitions (walls) liable to containing SWs at each floor, the algorithm has to find a distribution of structural SWs that would simultaneously satisfy a set of constraints and optimize the design or performance criteria. At first step, a set of random potential solutions which satisfy the imposed constraints is generated and called initial population. The set will then evolve towards a population of solutions that matches better the criteria. The evolution consists of series of crossover between solutions followed by mutations, and keeping, amongst the newly produced solutions, those which fit better the performance criteria. The GA flowchart shown in the next Figure 4-9 illustrates the different steps of the Algorithm [28].
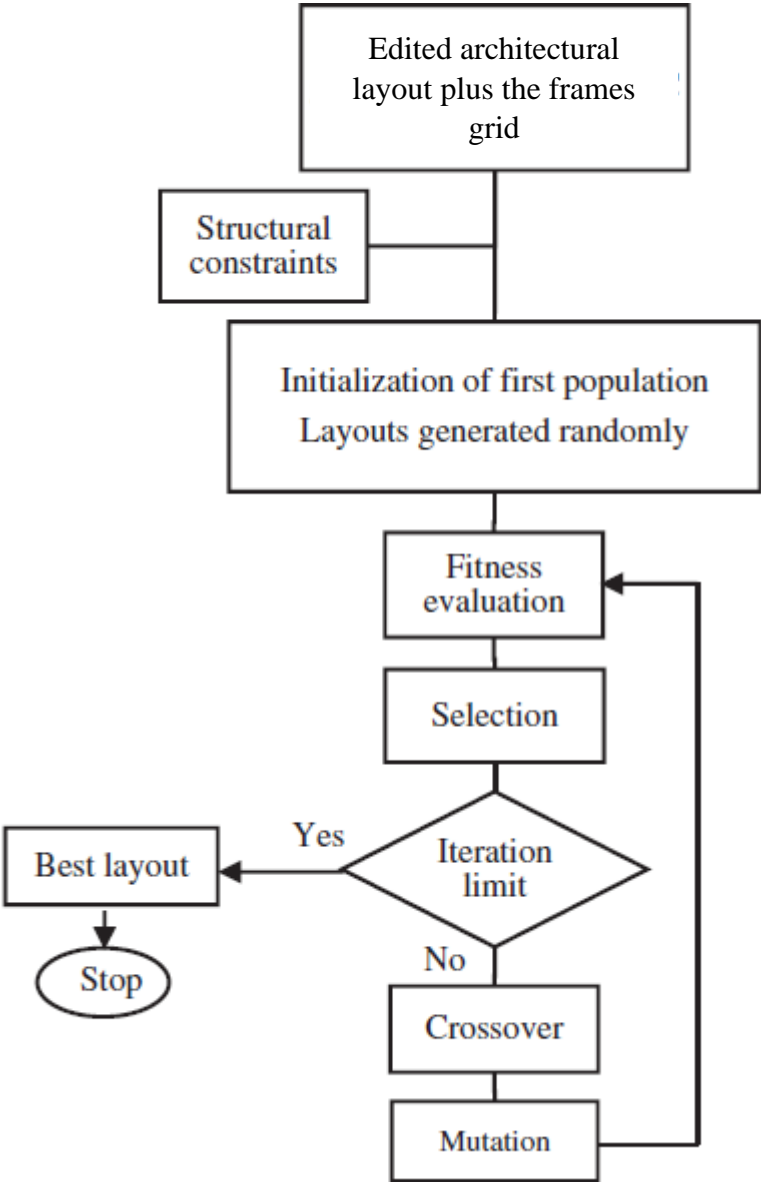

Figure 4- 9 Genetic algorithm flowchart

Edited architectural layout plus the frame grid: The walls in the architectural layout are limited only to those of which the axes are chosen by the Tabu Search algorithm and are

cropped to avoid the space where columns exist. In addition, the columns are considered in the calculations of the eccentricity and torsional radius so they have to be included.

4.4.1.2 Random generation of walls configurations

The Shear walls are generated following a normal distribution N (μ, σ^2) with the following parameters:

$$\mu = L_{opt}$$

$$\sigma^2 = L_{opt} - L_{min}$$

Eq. 15

Each Shear wall is positioned randomly within the edited architecture walls layout given in the BIM model geometry following a positioning probability slightly biased towards the edge of the slab contour so that it accelerates the convergence to the optimal solution.

For the present particular type of structural system (RCDS), a solution generated by the GA needs to satisfy the following set of constraints:
- Minimum length of each shear wall
- Limited architecture wall distribution (layout)
- Load path continuity

4.4.1.3 Crossover function

Crossover is an operator that allows the combination of the genetic material of two or more solutions [29].

Crossover is a significant phase in a genetic algorithm. For each pair of parents to be mated, a crossover point is chosen at random from within the genes.

A solution is generated from two existing configurations (Figure 4- 10) by selecting walls from the first solution and completing the remaining from the second; this will allow the new solution to inherit characteristics of both parents without violating the constraints listed above.
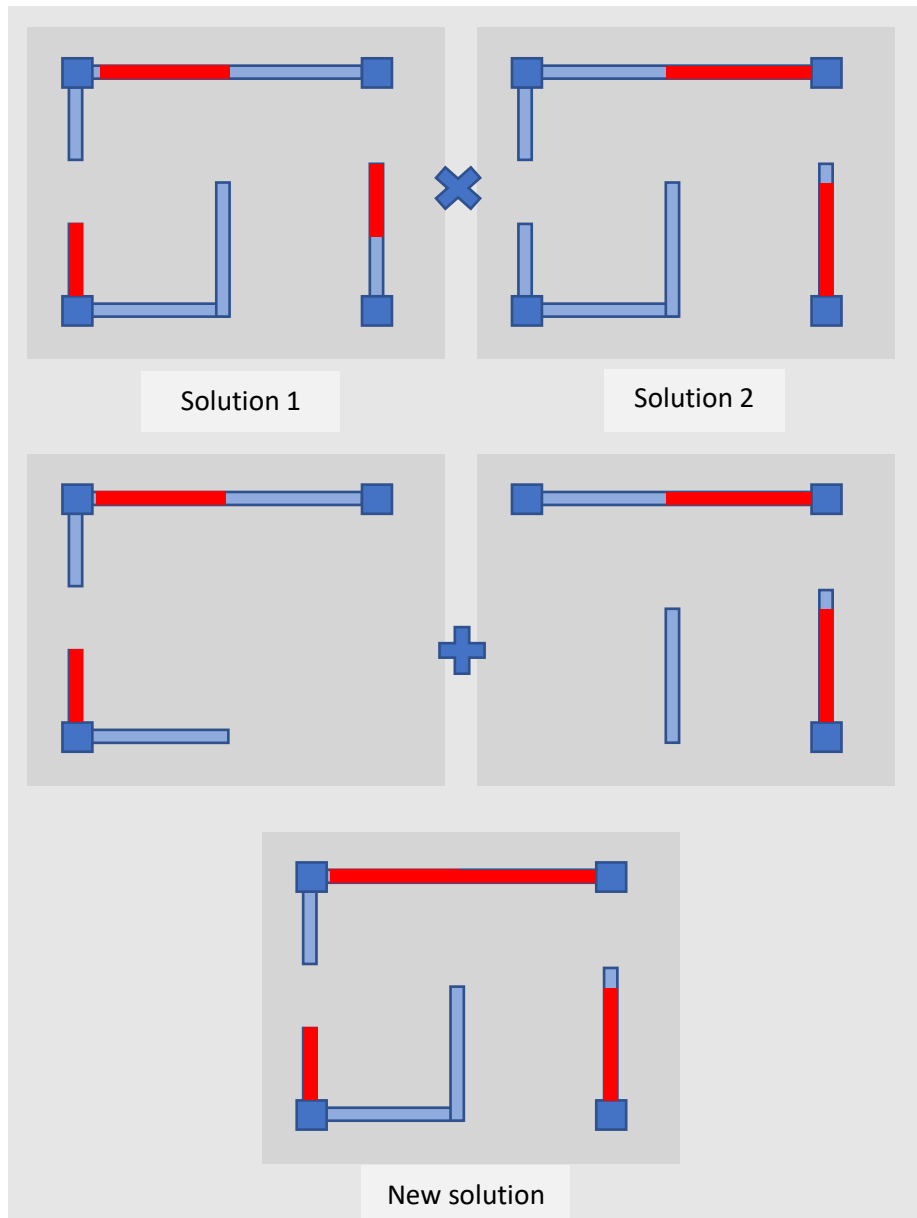
Figure 4- 10 Cross over operation

4.4.1.4 Mutation function

Mutation operators change a solution by disturbing them. Mutation is based on random changes [19].

The newly generated solution from the crossover has a probability of mutation, which is an empirical parameter given as input to the algorithm, through which one of the walls is slightly changed. Two types of mutations are considered:

- Adding shear wall length: it might be an extension to an existing shear wall if this one has not yet reached the maximum length allowed or a newly inserted shear wall fig4-11.
- Reducing shear wall length: either an existing shear wall is shortened if it has not yet reached the minimum length allowed or it is removed completely (fig 4-11).

The purpose of mutating solutions is to explore new possibilities and avoid the limitation set by the original characteristics generated randomly by the algorithm.
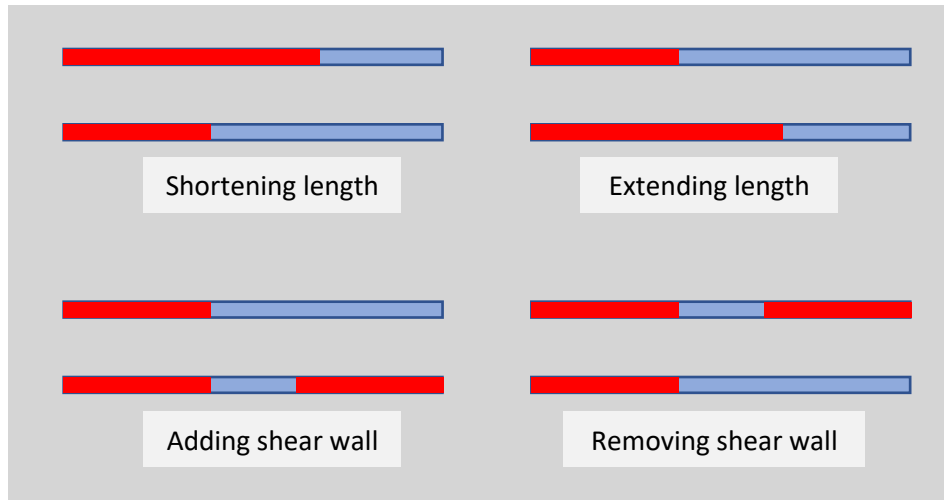

Figure 4- 11 Mutation operation example

4.4.1.5 Formulation of the objective functions:

Much like the Tabu Search algorithm, for the GA, the fitness function determines how fit an individual is (the ability of an individual to compete with other individuals). It gives a fitness score to each individual. The probability that an individual will be selected for reproduction is based on its fitness score.

In order to move the population towards the optimal solution, a fitness function is required in order to evaluate how close the solution is to an optimal. First, for any given solution each criterion is evaluated independently, that is:

- Floor Torsional eccentricity (Symmetry): The torsional eccentricities e_x and e_y, are normalized to 1 for a perfectly symmetric solution and 0 refers to a given limit eccentricity or an eccentricity equal to the maximum allowed by the regulations in plan dimension of the slab.

$$e_x < 0.3R_x \quad and \quad e_y < 0.3R_y \quad [14]$$

$$Score_{Ex} = 1 - \frac{e_x}{(0.3R_x)} \quad and \quad Score_{Ey} = 1 - \frac{e_y}{(0.3R_y)}$$

Eq. 16

- **Covered floor area:** To comply with the condition from the regulations, shear walls should carry no more than 20 percent of the vertical loads. This is estimated by relying on the area of the floor the shear wall is estimated to cover based on the results to approach to this area explained in the second chapter. The score of this area is calculated so a result of 1 represents exactly 20 percent of the total slab area covered by the shear walls, if it exceeded this limited it will be penalized. The score formula used to ensure that is:

$$If \ A_{eff} > 0.2 \ A_{slab}: \qquad Score_{area} = \left(\frac{0.1A_{slab}}{A_{eff}}\right)^3 \qquad \textbf{Eq. 17}$$

$$Else : \quad Score_{area} = 1 - \frac{0.2A_{slab} - A_{eff}}{0.2A_{slab}} \quad \textbf{Eq. 18}$$

Where:
- A_{eff} is the effective area shear walls cover as illustrated in Figure 4- 12.
- A_{slab} is the total area of the slab.
The overlapped area is counted only once as effective area.

- **Overlapped area:** For better spacing, and to avoid a negative effect the area approach adopted, overlapped area is to be reduced as much as possible through its score:

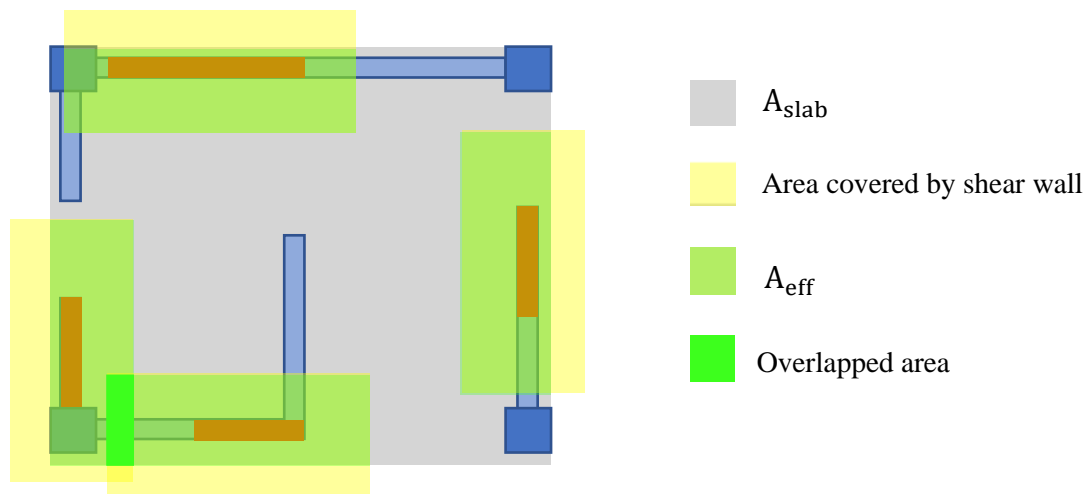$$Score_{overlapped} = 1 - \frac{A_{overlapped}}{A_{slab}} \quad \textbf{Eq. 19}$$

Figure 4- 12 Effective area covered by SWP

- **Distribution:** In order to achieve a better shear wall distribution in both directions and avoid having more important SWP quantity in one direction than the other. A parameter of the quotient between shear walls length in both direction is L_x and L_y considered. For a perfect distribution in both directions, the score is equal to 1 and the worse it is the lower the value will be:

$$Score_{distr} = \frac{\max(L_x ; L_y)}{\min(L_x ; L_y)} \quad \textbf{Eq. 20}$$

- **Short beams:** To avoid having short beams that can be endangered by the high shear effect of the lateral load. A distance between load bearing elements should be respected:

$$Score_{SB} = 1 - \frac{N}{2n_{swp}} \quad \textbf{Eq. 21}$$

Where: N is the number of the cases where the distance is not respected and n_{swp} is the total number of SWP.

- The torsional radius needs be maximized in order to have an optimal wall distribution. Shear walls are ideally put in the external walls of the building to maximize the torsional

rigidity, this parameter allows the algorithm to generate more external shear walls. The torsional radius is compared to I_s (the radius of gyration of floor mass in plan)

$$I_s < R_x \quad and \quad I_s < R_y \quad [14]$$

$$Score_{Rx} = 1 - \frac{I_s}{R_x} \quad and \quad Score_{Ry} = 1 - \frac{I_s}{R_y}$$

Eq. 22

4.4.1.6 Selection

The idea of evaluation phase is to select the fittest individuals and let them pass their genes to the next generation. The individuals are selected based on their fitness scores. Individuals with high fitness have more chance to be selected for reproduction.

Finally, an evaluation vector v of each criterion is generated. The fitness value of a solution is defined as:

$$f_v = \text{v. w}$$

Eq. 23

Where w is a constant weight vector defined empirically, that is each criterion has a weight proportional to its importance in evaluating a solution.

4.4.1.7 Termination

The termination condition defines, when the main evolutionary loop terminates. Often, the Genetic Algorithm runs until the objective function value has reached a certain pre-defined value [18]. This can be reasonable in various experimental settings.

To ensure robustness, a specific value for the eccentricity score is given as a stopping condition. While it was assigned a lower weight than other scores so that when the value for the eccentricity reaches the stopping value, other scores have already improved enough.

4.5   Conclusion

In this chapter, two different algorithms were exploited to generate an optimized configuration of an RCDS based on the architectural layout as an input.

The Tabu Search algorithm is used to propose an optimized frames' grid starting from a randomly generated grid that follows certain constraints which serves the rapid convergence. A limited loop evaluates all possible neighbors of the solution processed during that iteration through a number of evaluation criteria. The solution considered for the next iteration is the best of the neighbors in the previous iteration until the latest iteration is reached.

The concept of the GA is also based on a multi-objective optimization process that randomly generates an initial population of potential SWP configurations, which comply with architectural constraints in addition to the previously generated frames' grid, matching a set of general structural guidelines and seismic design rules. The initial population evolves through series of crossover between current solutions (parent) followed by mutations generating new solutions to be adopted, for the next iteration, when they improve the performance criteria.

Note: Having six different objectives rises some difficulties finding a compromise that leads to satisfying all conditions. This issue and others will be thoroughly treated in the next chapter.

Chapter 5: Testing, Tuning and Validating the Results

5.1 Introduction

The two stages optimization procedure is relatively complex because of the numerous parameters of the multi-objective function and the stringent constraints.

This chapter goes through adjusting the program's parameters and shows unsatisfying results on the way doing that until final results are reached and robustness is achieved.

Finally, a finite element model of two of these models are tested on ETABS to verify their compliance with the regulations.

5.2 Architectural layouts

Three different architectural layouts (Figure 5- 1, 2 and 3) are used in order to test the performance and the sensitivity of the GA. The architecture samples are selected according to the following parameters:
• The geometrical dimensions (surface, height)
• Locations of the openings (windows, doors)
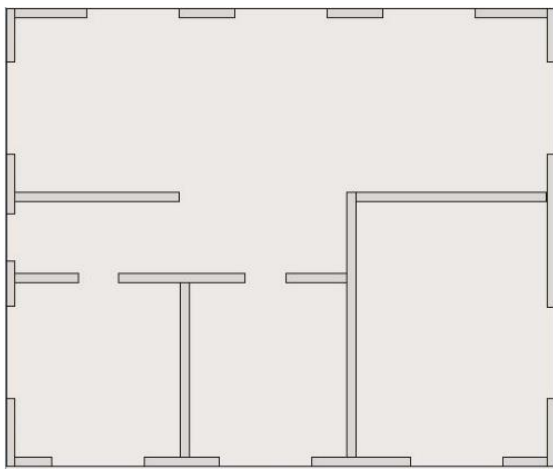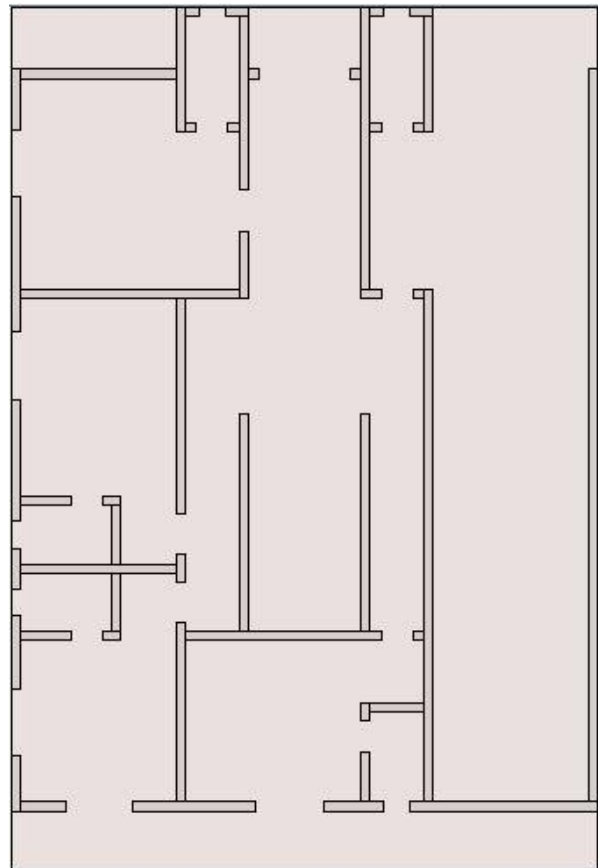• Layout of the inner and outer walls

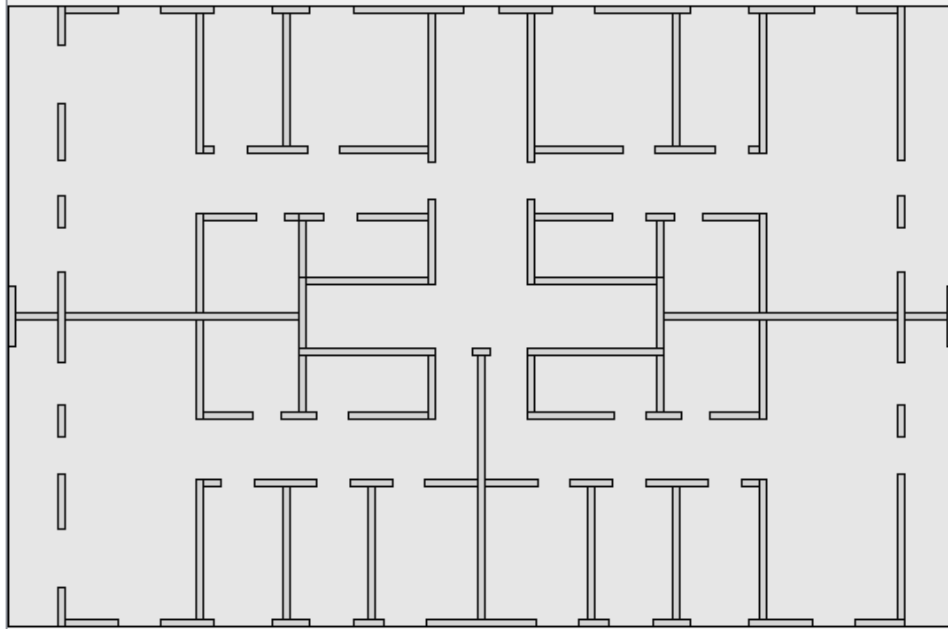Figure 5- 2 Model (1)

Figure 5- 1 Model (2)

Figure 5- 3 Model (3)

The 3D architectural configurations are derived from realistic reinforced concrete projects. They are adjusted using the software Autodesk Revit version 2021.

5.3 Determination of the columns' positions

The TS algorithm converges towards the most optimized frames system out of all possible axes to choose from. The results of this part of the program are unique to each model, which confirms the robustness of this part of the program.

Sometimes, it seems to give a different result for the model but in fact they are mirrored configurations and they have exactly the same properties.
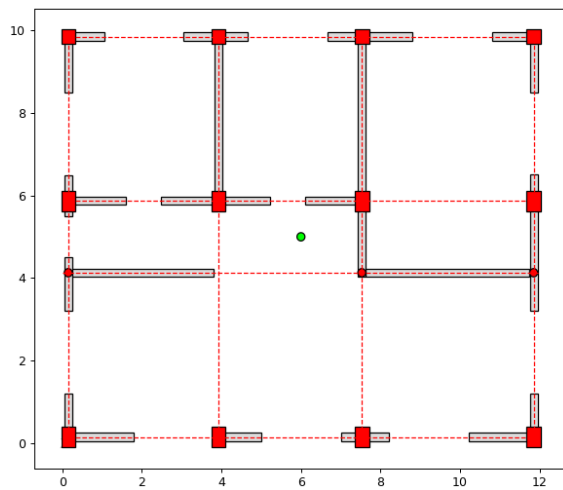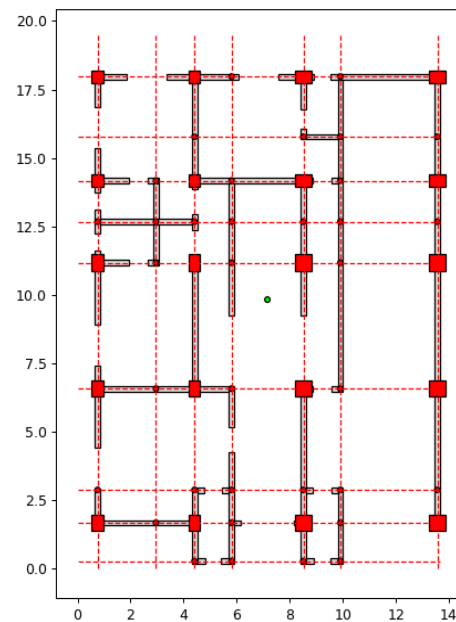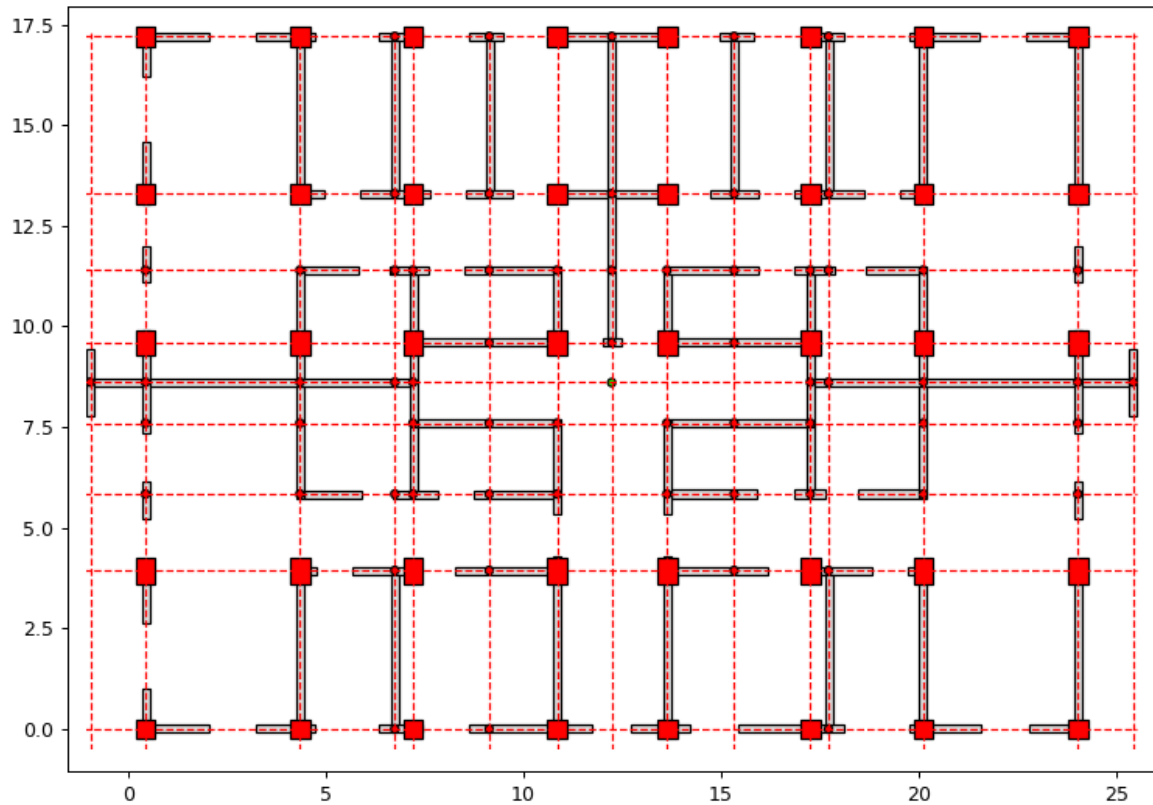

Figure 5- 4 Model (1) columns result

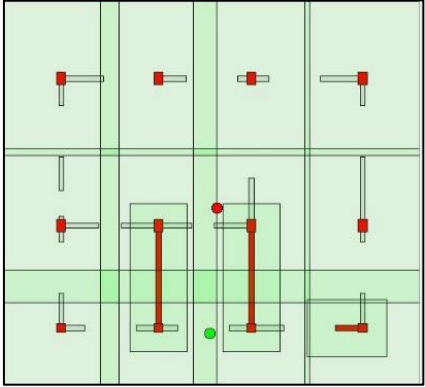
Figure 5- 5 Model (2) columns result
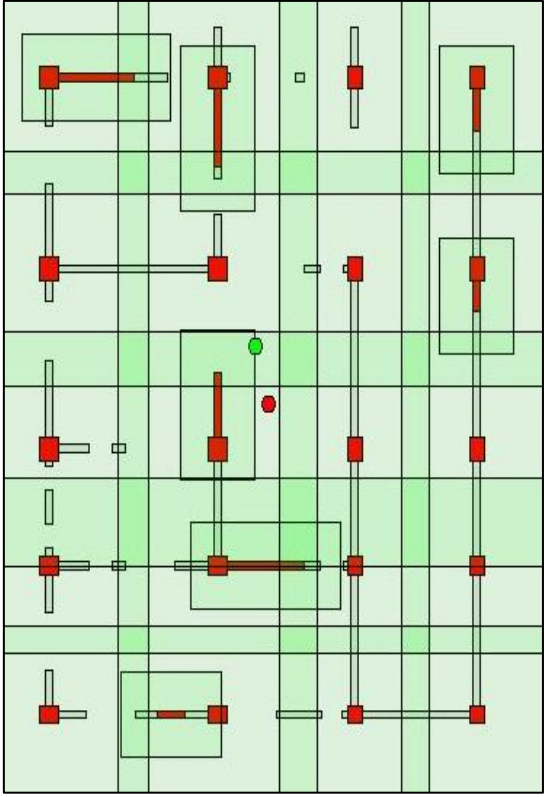
Figure 5- 6 Model (3) columns result
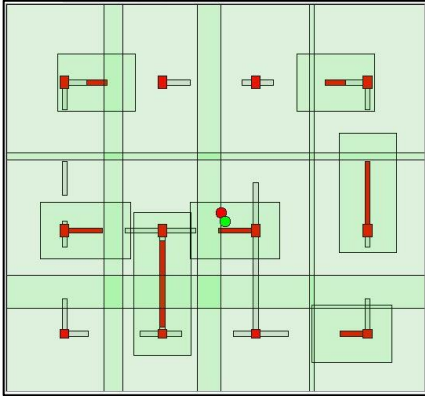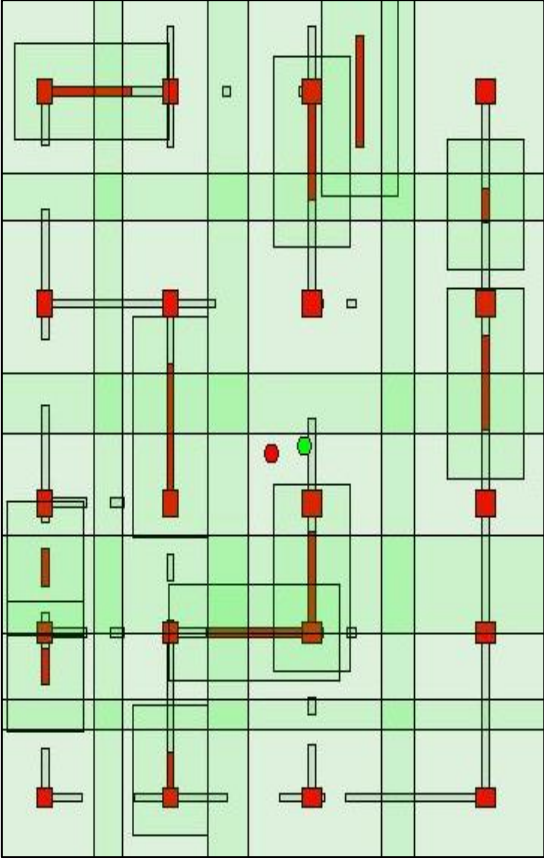
5.4 Refinement and Tuning of the GA Parameters

The output layouts of the GA respect totally the architecture interior partitions at all levels. The shear walls were positioned in agreement with all the openings (windows and doors). The load path condition of the walls has also been satisfied for all the configurations. As for the rest of the conditions that were enforced by the fitness scores of each one them, multiple trials were required to achieve the tuning of the weights.

Since we have six different parameters controlling the objective function, it is very difficult to tune them simultaneously. Therefore, only four parameters (table 3) are considered for the sensitivity analysis.

In each try, to observe the behavior of the GA, one objective function is given a small weight compared to other scores to see if it truly functions the way it is supposed.

Table 2 Tests on the objective functions

	Eliminated O.F	Model 1	Model 2
1	Eccentricity		
2	Area		

3	Overlapping		
4	Distribution		
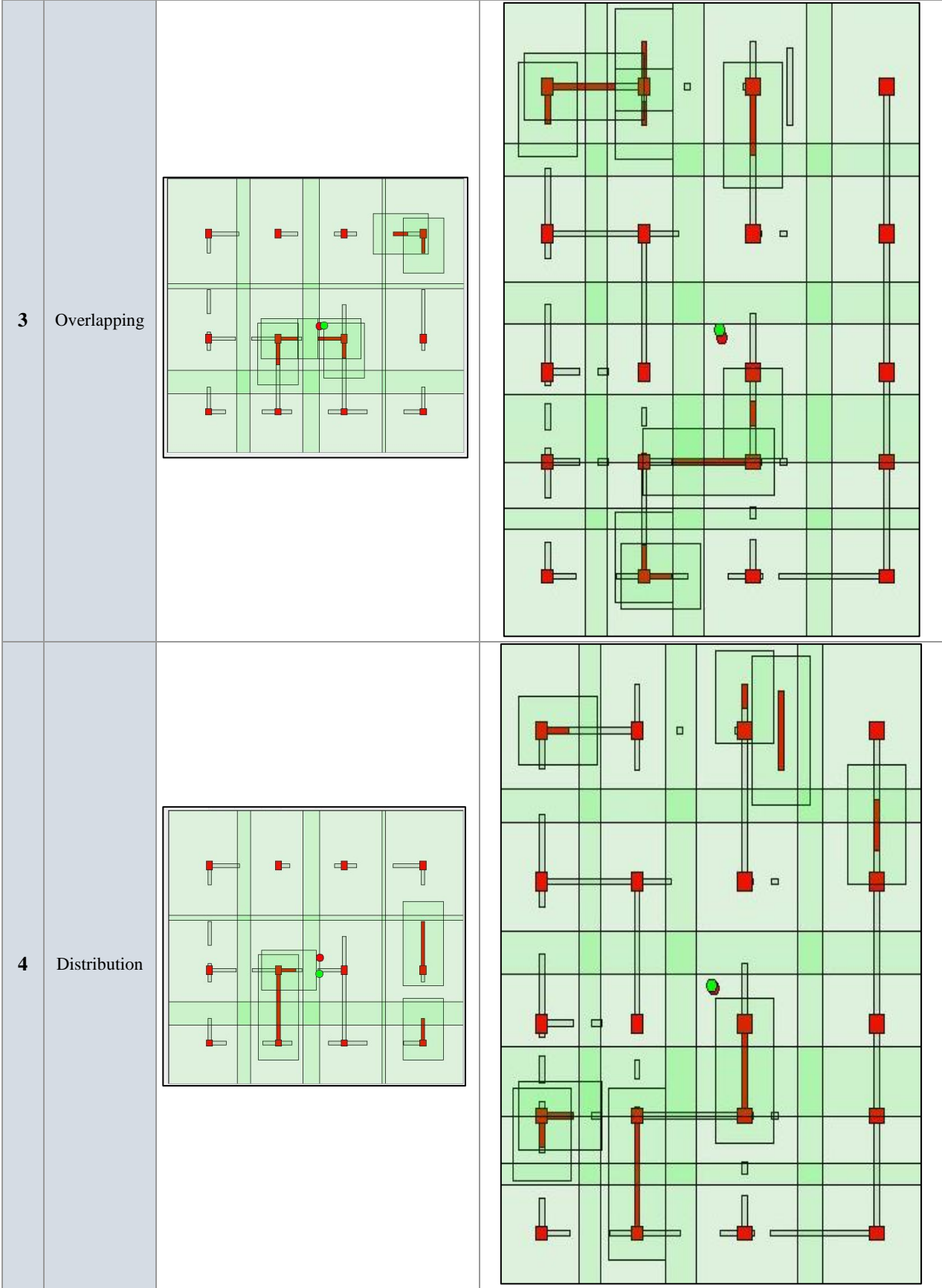
We noticed that by activating simultaneously all the parameters of the objective function with a considerable weight, the result becomes unpredictable. Table 2 and Table 3 prove that launching the program with a focus on three objectives while the others are deactivated with a minimal weight will approach a better solution that satisfies all other criteria except the deactivated one.

The Table 3 visually illustrates the pattern observed by launching the program for a limited number of iterations. All scores are limited to 1 for a perfect case, some do not have a lower end (might be negative in worse cases) while other are limited by 0.

Table 3 Scores of the tests on the objective functions

Test	Score \ Model	Eccentricity	Area	Overlapping	Distribution
1	1	-1.05	1	1	0.91
	2	-0.33	1	1	0.97
2	1	0.71	0	0.99	0.87
	2	0.45	0	0.9	0.33
3	1	0.75	0.97	0.48	0.93
	2	0.79	1	0.73	0.89
4	1	0.74	0.94	0.68	0.1
	2	-0.33	1	0.9	0.15

These results show that some criteria, if deactivated, might effect other criteria as well. For example, deactivating the distribution (test 4) resulted in having a negative score for the eccentricity.

It is observable that deactivating the eccentricity came out with results perfectly satisfying the other criteria, however, it is not adequate to not consider an important factor such as the eccentricity. Therefore, the solution to this was to use it with a minimal weight to allow other criteria to converge while having this latter as a stopping condition. At the end of the program's loop, not only the area, overlapping and distribution scores are perfect but also the eccentricity, because the program will keep on running until its score reaches a specified enforced goal.

Since the results are as expected for all the eight trials, we can conclude that the robustness of the program is verified.

5.5 FE analyses of optimized structures

The optimized structures are modeled and analyzed using ETABS in order to validate their compliance to the regulations in terms of lateral and vertical loads as well as the actual center of mass and rigidity for each of them.

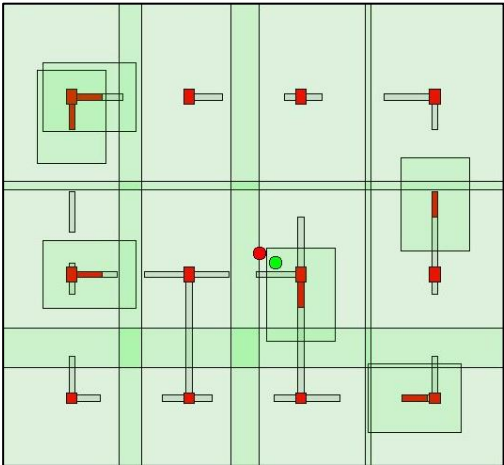Table 4 Layouts generated by the program and the corresponding FE models
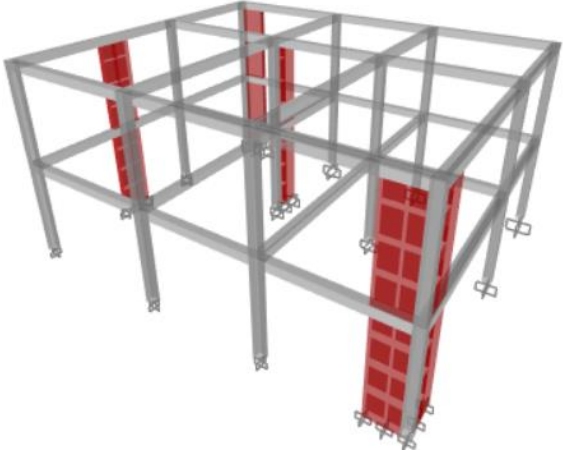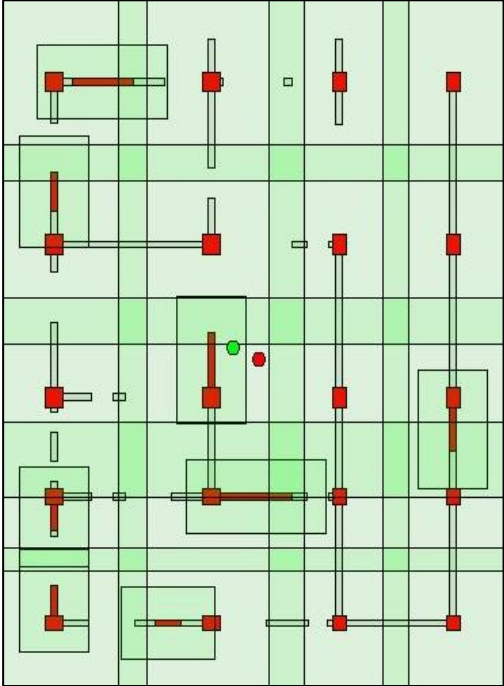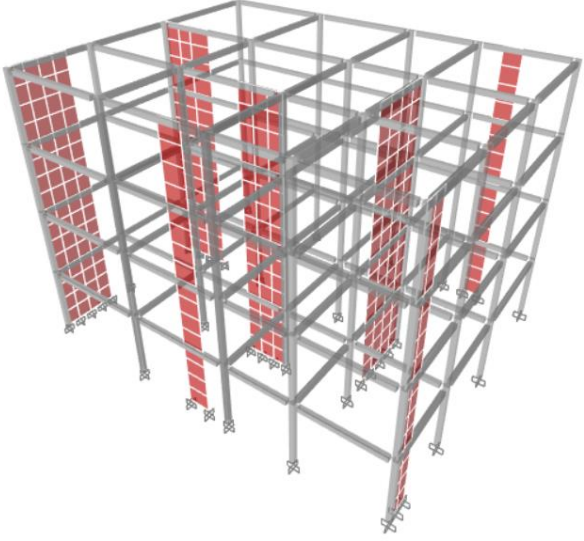
N°	Layout view generated by the program	Structural FE model
1		
2		
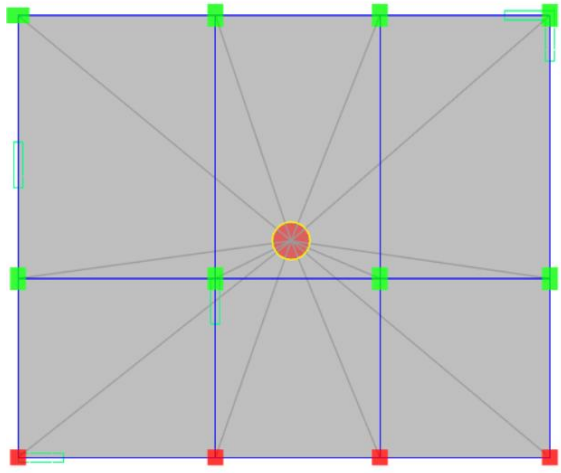
Table 5 Scores of the results

Score \ Model	Eccentricity	Area	Overlapping	Distribution
1	0.94	0.91	0.93	1
2	0.7	0.96	0.99	0.87

5.5.1 Eccentricity

Because the program runs on approximate functions, the presence of slight differences from the actual results are predictable but they remain insignificant, and the results are admissible where the condition $e_x < 0.3R_x$ by the regulations is verified.

Table 6 Finite elements models eccentricity by level

Model	FE model view of the top level	Mass center	stiffness center	ex, ey
1		(5.8; 4.9) (5.6; 4.7)	(5.4; 4.7) (5.1; 4.5)	$e_{x1} = 0.4$ $e_{y1} = 0.2$ $e_{x2} = 0.5$ $e_{y2} = 0.2$

| 2 | | (6.2; 8.1)
(6.3; 8.7)
(6.3; 8.7)
(6.2; 8.7) | (6.2; 8.2)
(6.2; 8.0)
(6.1; 8.8)
(6.1; 8.7) | $e_{x1} = 0$
$e_{y1} = 0.1$

$e_{x2} = 0.1$
$e_{y2} = 0.7$

$e_{x3} = 0.2$
$e_{y3} = 0.1$

$e_{x4} = 0.1$
$e_{y4} = 0$ |

5.5.2 Gravity load distribution

To verify the conditions of gravity load distribution among the walls and the frame, the reactions at the base are calculated and compared on Table 7.

Table 7 Tests of the vertical loads

Model	Structure	Vertical forces (KN)	Total (KN)	Percentage
1	Shear walls	597.0708	3056.7829	19.5%
	Frames	2459.7121		80.5%
2	Shear walls	3144.6199	13271.1718	23.6%
	Frames	10126.5519		76.4%

Table 7 shows that the walls bear about 19.5% and 23.6% of the total gravity load of model 1 and model 2 respectively, which is in compliance with RPA99v2003 for dual system

5.5.3 Lateral load distribution

Table 8 shows the lateral load distribution of the total horizontal (seismic) loading as resisted by the frame and the SWs.

Table 8 Tests of the horizontal loads

Model	Structure	Lateral forces (KN)		Total (KN)		Percentage	
		X	Y	X	Y	X	Y
1	Shear walls	262	280	373	378	70%	74%
	Frames	111	98			30%	26%
2	Shear walls	1264	1166	1560	1576	81%	74%
	Frames	296	410			19%	26%

In this case, for the first model, the frames received a total of 30% and 26% in the X and Y directions respectively, which are higher than the 25% that they should be capable of resisting, this implies that the condition is verified. It is the same situation for the second model in the Y direction, however, in the X direction the frames received 19% but they still might be capable of resisting the 25 %.

5.6 Conclusion

After analyzing the different results, and adjusting the algorithm, it is noted that:

- The TS algorithm functions near to perfect, and the results showed that the algorithm is stable and robust.
- The selected parameters of the objective function gave satisfying results, and their effect can be controlled through adjusting the scaling factors values.
- The algorithm has good overall performance, and it can be used as a tool to help determine and optimize RCDS layouts.
- The use of artificial intelligence tools can ease the process of building design, which results in a better productivity.

Conclusion

The main objective of this study was to integrate a design system of RCDS structures to a BIM platform and simulate the way that an engineer would proceed to design it starting from a given architectural configuration. An integration that enhances the productivity with the improvement of the knowledge sharing and interface between disciplines involved in the whole construction process.

The automatic design procedure based on TS and GA algorithms was adapted so that for a given architectural model on a BIM platform using the IFC protocol, the algorithm defines the slab elements and the architectural walls layout on each floor.

The Tabu Search algorithm relies on having all axes of the existing walls in the architectural layout. A random first solution that follows certain constraints is created then a list of all possible neighbors are evaluated to select the fittest based on multiple scores. This step is repeated until the final iteration.

The GA's role begins after the TS because its result is needed to ensure satisfying the interaction between the frames and SWs is respected. A set of random potential solutions which satisfy the imposed constraints is generated. This set will then evolve towards a population of solutions that matches better the criteria. The evolution consists of series of crossover between solutions followed by mutations, and keeping, amongst the newly produced solutions, those which fit better the performance criteria.

It turned out that the outcome layouts are very sensitive to the weights of the objective functions, in addition, having a lot of objective functions made it hard to control solely through weights. It was extremely challenging to fix the appropriate weight of each objective function without amplifying its effect and affecting the other parameters of the objective function. Therefore, judicious approach to control it by using the eccentricity as a stopping condition is derived after conducting multiple tests.

An important implication of this research to the entire process of design and construction of reinforced concrete dual systems is to help automatize the interface between disciplines especially architecture and structural engineering which can be easily implemented in a BIM environment. Finally, the proposed approach is open to future enhancement of the algorithm to integrate more or updated code requirements related to the RCDS. As a perspective research work, the results can be enhanced further using alternatives that are more realistic than the approaches used like the covered area by the shear walls or the dimensioning of the column. For even further enhancement, linking the program with testing software like SAP or ETABS for instant evaluation of the results during the optimization.

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