Optimization Approaches for Standard Repairs in a Concrete Element

Master Thesis by:

Alireza Amirfiroozkoohi

Supervisor:

Dr. Jesús Miguel Bairán García

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Universitat Politècnica de Catalunya, Barcelona Tech
Departament d´Enginyeria de la Construcció

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I would like to extend my love to my parents for believing in me and supporting me in every possible way. My gratitude to them is boundless.

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Abstract

This study investigates the optimization approaches for standard repairs in a concrete element. A methodology for automatic optimize and cost estimation of common elements will be developed by MATLAB programming, which is useful for decision making in performance-based design. The study indicates that after extreme cracking in the building, what are the optional ways to repair and reinforce the construction. In addition, it shows what type of repairing is much better than the other ones.

The most significant information for decision-makers would be the cost to retrofit a building. The objective is to provide fertile ground for the decision-makers with accurate information when deciding whether to mitigate or to permit the building to remain as built. In order to achieve such an important goal, an excellent knowledge of knowing about repair and retrofit costs are needed. Indeed, evaluation of repair and retrofit costs play a pivotal role in the future of concrete structures.

The real plan is used from kermansha city in Iran. The concrete removal methods, surface preparation methods, coating material, and reinforcement materials brought in the concrete repair guide “ACI 546R-04, And Federal Emergency Management Agency (FEMA) was published FEMA 273 and FEMA 274 as two guidelines for seismic rehabilitation of buildings. After that, FEMA 356 entitled of “Pre-standard for Seismic Rehabilitation” were released based on FEMA 273 and 274. It was intended to be used as a relevant source for professional designs, code officials, and building owners to undertake the seismic rehabilitation of structures.

The analysis results have been presented and discussed. All the numbers, including weights, constraints, and coefficients, could be changed if needed. The purpose of this study is not to offer a series of solutions for a specific building but to propose an optimization approach to reach the best solutions possible in a situation. All the charts and tables representing the results including Pareto fronts are presented.

Table reference

Figure reference

Chapter 1: Introduction

1. Background

Generally, natural disasters such as earthquakes, hurricanes or floods are considered as discrete events, which may occur during a structural lifetime, in a geographical area, influence inhabitants and cause extremely noticeable direct and indirect losses. Although natural disasters remain as probable hazards which threatening human lives and causes economic losses, human actions can also be influential. These actions could increase or decrease the vulnerability of societies to natural and unnatural disasters.

In order to manage the mentioned risk due to the natural disasters, it is necessary to evaluate and account for the threatening potential of a natural disaster which would be subjected to people and assets then finally, obtaining a vulnerability assessment of exposed assets.

In many cases, there is not so much option for reducing occurrence and probability of natural disaster; therefore engineering solutions should be focused on strengthening existing building in order to reduce the probable damages caused by disasters.

These probable damages have been increased during recent decades due to the higher rate of urbanization. Quantification of these losses could be achieved using a risk-based technique which could be obtained by some components such as vulnerability, fragility, and hazard. Risk management procedure which is conducted for this goal would be including some associated elements like; the risk identification and risk mitigation procedures.

Risk definition refers to the probable direct and indirect losses caused by a hazard while vulnerability and hazard functions are defined as a conditioning function of the probability distribution of loss ratio and an intensity measure as input and representation of the annual occurrence probability of specific intensity measures (IMs), respectively. Structural risk mitigation procedures could be consisting of any actions that require the construction to reduce the effects of a disaster, such as seismic retrofitting.

Importance of structural risk mitigation procedures could be understood by considering past earthquake disasters occurred in the world. In recent decades the average population which was influenced by natural disaster risks was increased from 60 to than 179 million in 1985 to 2014.

Individually, earthquake as an extreme event could be considered as one of the most threatening events subjected to structure. Seismic damages play a prominent role in natural disaster losses.

Sumatra, Indonesia was experienced an earthquake with 9.1 magnitude 2004 in which causes more than 200,000 deaths. Kocaeli and Düzce (1999) earthquakes cause considerable damage to residential and commercial buildings, public facilities and infrastructure and significant casualties and injuries in turkey. Haiti has suffered from a violent earthquake in 2010, which caused more than 200,000 deaths. In Iran, Gilan 1990 earthquake and recently Kermanshah 2018 caused tens of thousands of fatalities and considerable economic losses. There are some other destructive earthquakes such as the 1995 Kobe, the 1999 Chi-Chi, the 2004 Mid Niigata and the 2008 Great Wenchuan earthquake which had effected people lives and assets.

2- General statement of the problem

If such violent earthquakes affect residential areas of infrastructures of a city, it will cause enormous direct and indirect losses for inhabitants and authorities. This would be a significant concern for any seismological area around the world that could take place in the future. In order to control or reduce these catastrophic effects of earthquakes, some methodologies have been developed. Designing structures based on their performance are one of these methodologies. This designing approach allows engineers to restrict the seismic risk in structures into an acceptable or moderate socioeconomic level.

According to this viewpoint, natural disaster risk management would be able to give a chance to reduce these adverse effects for any area all around the world. Natural disaster risk management could be defined as the procedure of identification, analyzing and finally estimation the occurrence probability of the losses which could be used to facilitate the decision-makers to perform preventive actions.

In order to prevent these losses through risk mitigation procedures, there are some practical approaches which could be applied in existing buildings. These approaches are subdivisions of retrofitting technique. Retrofitting would be referred to defining the procedures which have done during strengthening, remodeling, and repairing methods. Retrofitting techniques have been widely used in order to enhance the seismic performance of reinforced concrete structures. For example; using carbon fiber reinforced polymer (CFRP), column jacketing, column strengthening, enlargement, base isolation, using energy dissipation devices, Mass reduction, etc. are some of retrofitting approaches.

For making a decision what kind of retrofitting techniques must be employed for each structure, all of the available options have to evaluate from both economic and engineering point of view so that the authorities could decide adequately.

There are some techniques for evaluating the cost of a project from site issues into retrofitting such as Life Cycle Cost Analysis or Benefit-Cost Analysis. For this purpose, this dissertation focused on a MATLAB-based developing code in which there are three main objectives. These objectives are price, compatibility, and durability and there are also constraints for each objective that should be satisfied. The developed MATLAB code imports data from database files which are made of the values in excel format. A simplified single objective problem had been used to develop the pre-mentioned code. The decision-maker and authorities should enter the weight for each objective function concerning its importance. Then the code minimizes the single objective matrix for ten iterations (or more). Finally, the Pareto front will be shown to each objective in 3D and 2D spaces.

Using the assessment of cost and benefits from this viewpoint, it could be concluded that retrofitting is an economically practical solution as a risk mitigation option. Based on this study and using the developed MATLAB code, this would be feasible for decision-makers and structural owner to choose from available different option of retrofitting techniques.

3- Objectives

3-1 Overall objective

According to the pre-mentioned problem-related to catastrophic seismic effects, this dissertation mainly focused on obtaining a reliable design and cost assessment of structural repairs in concrete elements. The cost of retrofitting process is essential information for decision-makers. Since repairing processes of damaged structural elements are needed after extreme events, the main object of the current thesis would be practically useful in seismic risk mitigation projects for RC building. For this purpose, this thesis investigates standard repair approaches in a concrete element which is a methodology consists of automatic design and cost estimation of structural elements.

3-2 Specific objectives

Besides the main objective of the dissertation, there are some more specific defined objectives for this study. Some of them are summarized as follows;

Investigating the design approaches for typical repairs in RC elements
Automatic design of structural elements
Cost estimation of structural elements
Developing a MATLAB code using a simplified single objective problem
Quantify the cost of structural repair
Value repair strategies and costs
Optimize the seismic design strategy for the structure studied, considering the costs

Facilitate decision making for performance-based designers

This thesis is aimed to conclude some financial results for repairing techniques in order to encourage authorities, decision-makers, and people to take use risk mitigation strategies against the earthquake and reduce the potential vulnerability of residential and public RC structures.

4. Methodology

In order to provide accurate information for local and governmental authorities and facilitate their decision-making process for whether to run mitigation process or not, excellent knowledge of repair and retrofitting techniques and their associated cost are needed. Therefore, to fulfill the predefined overall and specific objectives set of this dissertation, the following procedure is employed;

Firstly, some of the most common practical techniques for repairing structural elements would be investigated. These techniques and their associated financial aspects are considered thorough a computer program. For this purpose, a MATLAB-based code had been developed in which there are three main objectives. These objectives are consisting of price, compatibility, and durability and there are also constraints for each objective that should be satisfied.

The developed MATLAB code works using a prepared excel database. The code had been developed based on simplified single objective problem approach. The decision-maker should enter the weight for each objective function according to its importance. Then the code minimizes the single objective matrix for ten iterations (or more). Finally, the Pareto front will be shown to each objective in both 3D and 2D spaces.

5- Outline of the thesis

This dissertation consists of 5 main chapter chapters which are categorized as follows;

Chapter 1 introduces the general concepts of the dissertation consists of; Background: This part is related to the general background of the current dissertation included the effect of natural disasters especially earthquakes on the structures in form of direct and indirect losses. General statement of the problem: it is a part in which the main problem would be stated. Objectives: This part would be illustrating the main and specific objectives of the dissertation Methodology: This part consists of explanation of the specific methodology which had been used in this dissertation in order to fulfill the predefined objectives Outline of the thesis: this part would draw the main structure of the thesis.

Chapter 2 presents the literature studies consists of; General background on natural disaster risk and their adverse effects on the structures. Risk management and risk mitigation procedures, Retrofitting process.ATC-40 suggestions for seismic rehabilitation, Some standard method included a) using carbon fiber reinforced polymer (CFRP), b) column jacketing, c) column strengthening, d) enlargement, e) base isolation, f) using energy dissipation devices, g) Mass reduction, etc.

Chapter 3 entitle of methodology presents the idea of developing MATLAB code based on three main objectives (price, compatibility, and durability) using excel database files in order to achieve cost estimation of structural elements. How to use A simplified single objective problem for developing the predefined code and how the decision-maker could enter their weighting for each implemented objective function according to its importance. There would also be a detailed explanation of the functionality of the MATLAB code and how it minimizes the single objective matrix.

Chapter 4 gives a result and discussion of the thesis findings. This chapter is formatted based on using developed MATLAB code for assessment of various repairing techniques to price, compatibility and durability objectives for an actual structural element. There are also some recommendations for future researchers.

Chapter 5 entitle of conclusion presents articulation of the main points of the thesis with clarity. It consists of a discussion of summarized findings which were presented previously in chapter 4.

Chapter 2: LITERATURE REVIEW

2-1-Definitions and risk associated components related to natural disasters

It is necessary to define the essential components and terminologies associated with risk assessment and management of natural disasters in order to achieve proper understanding of this dissertation. For this purpose, following components are defined:

2-1-1 Natural Disasters

Generally, natural disasters are considered as some discrete events, such as earthquakes, hurricanes or floods which might occur once or more in a structural lifetime, in a geographical area, influence inhabitants and cause extremely noticeable direct and indirect economic losses. In order to manage the mentioned risk due to the natural disasters, it is necessary to evaluate and account for the threatening potential of natural disaster which would be subjected to people and assets then finally, obtaining a vulnerability assessment of exposed assets (Erdurmuş, 2005).

As mentioned before, Natural hazards are some natural phenomena which could cause economic and non-economic losses to human, structures, and infrastructures. Natural hazards could be categorized as follows (Erdurmuş, 2005);

Geological Hazards: natural phenomena which directly caused by some geological activities such as earthquakes, landslides, and tsunamis.

Climatic Hazards: this component refers to such natural disasters which have an association with climate conditions like floods.

Environmental Hazards: natural phenomena related to environmental sources such as environmental pollution or deforestation

According to the higher rate of urbanization in the recent decades, the average population influenced by natural disaster risks was increased from 60 to than 179 million in 1985 to 2014 (Fraser et al., 2016).

It is also inevitably important to specify specific terms related to risk assessment of a structure caused by a natural disaster such as an earthquake event. For this purpose, some components such as Risk, vulnerability, fragility, risk mitigation, and assessment would be defined in the next.

2-1-2 Risk related components

‘‘Risk’’ may be defined as ‘‘the combination of the exceedance probability of an unpleasant event and its adverse consequences’’ (erdik, 2017). In other words, the term risk refers to the probable direct and indirect losses caused by a hazard. In other words, risk expressed as expected

losses (in probabilistic format) according to vulnerability and hazard exposure. This definition relies on probability of hazard occurrence, and it is associated with consequences (Smith, 2017).
Vulnerability functions are referred to the models of the susceptibility of an asset or assets subjected to earthquake hazard to incur structural or non-structural losses. Earthquake vulnerability is defined as a conditioning function of the probability distribution of loss ratio and an intensity measure as input. Vulnerability models could be applicable for economic estimation of losses where the loss ratio could be referred to the ratio of repair/replacement costs for any given structure (Erdik, 2017).
Seismic hazard analysis in a probabilistic format called (PSHA) is one of the essential phases in the Performance-Based Earthquake Engineering (PBEE) framework (McGuire 2004). Hazard functions as results of Seismic hazard analysis are representing the annual occurrence probability of specific intensity measures (IMs).
Based on the basic components of natural disaster risk, a conceptual procedure for natural hazard risk evaluation could be presented based on three main elements, hazard, vulnerability assessment and the integrated risk assessment (Du and Lin, 2012).
As it is depicted in Fig.2.1, a risk evaluation procedure relies on three mentioned components. According to this figure, hazard analysis should be carried out Firstly, then vulnerability analysis consists of 1) vulnerability assessment, 2) geographical environmental factor 3) socio-economic factors would be achieved. Finally, based on calculated hazard and vulnerability function, risk evaluation would be estimated.

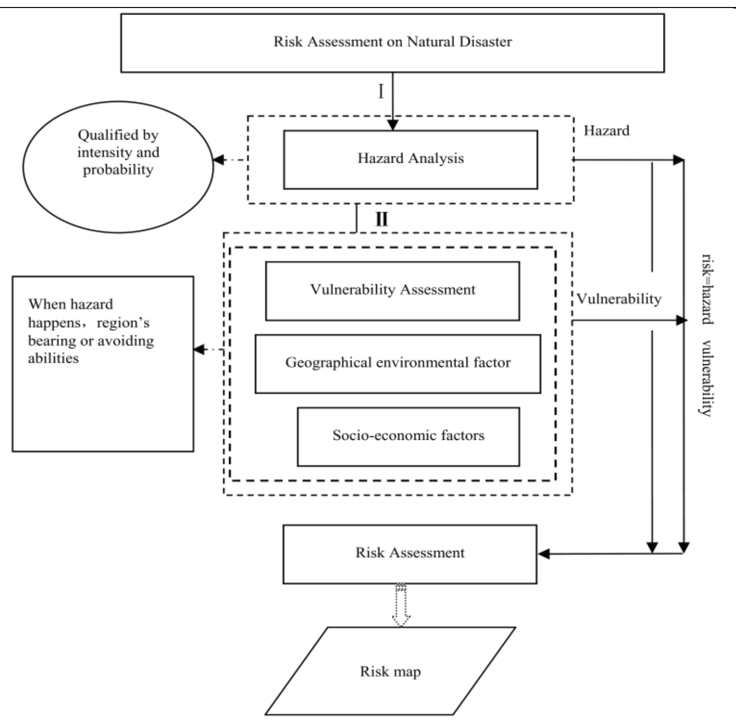


Figure. 2.1 Factors Determining Risk (Du and Lin, 2012)

As evident as it is, risk might be formatted for any natural disasters; thus, the risk definition would be defined for each natural disaster such as an earthquake event. In this specific example, seismic risk could be expressed as the probability that specified damage or loss would exceed within a given exposure time (structure lifetime) caused by an earthquake.

Risk assessment methodologies combine three main factors: earthquake hazard, fragility/vulnerability, and inventory of assets exposed to hazards. Also, there might be some other influential parameters entitled to capacity, as shown in Fig.2.2. These elements represent aleatory and epistemic uncertainties embedded in their components (Erdik, 2017).
Earthquake as an extreme event could be considered as one of the most threating events subjected to structure. Seismic damages play a noticeable role in natural disaster losses; therefore, it is important to consider the effects of such violent and extreme events on structures.

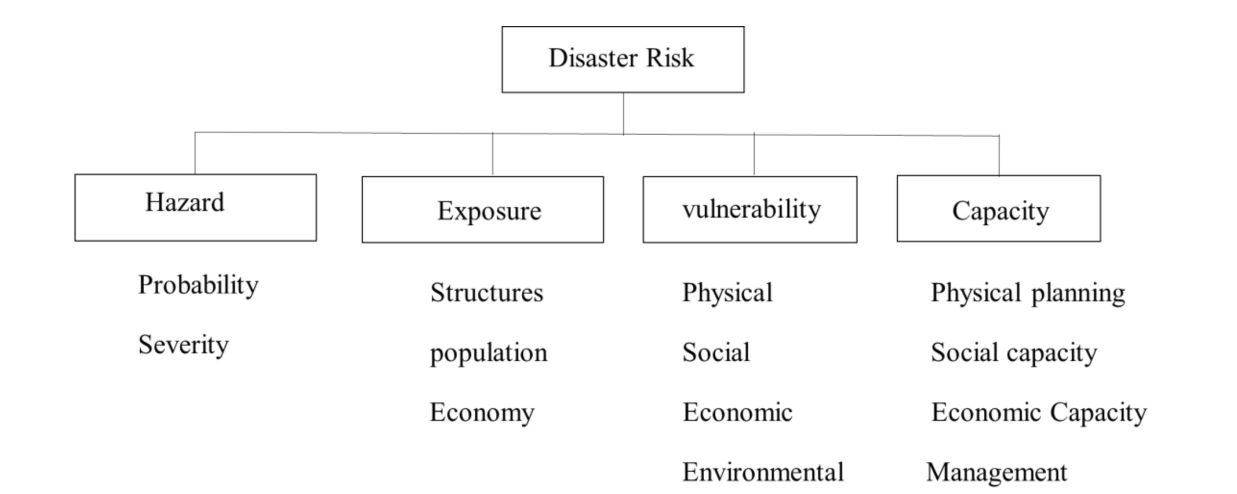


Figure. 2.2 Factors Determining Risk (Erdurmuş, 2005)

The assessment of disaster risk is the key step in disaster risk management, which includes a process of risk mitigation. Natural disaster risk management (NDRM) could be defined as the procedure of identification, analyzing and finally estimation the occurrence probability of losses which used to facilitate the decision-makers to perform preventive actions. The NDRM involves two main approaches as follows (Demeter 2005):
a) Using action plans in order to reduce vulnerability
b) Establishing protective mechanisms
The pre-disaster phase of disaster risk management includes four Components as follows (Demeter, 2005):
Risk identification: risk identification could be considered an analysis of existing vulnerabilities, location, the intensity of a hazard. Determining the causes of vulnerabilities might be helpful to reduce or eliminate them. This would be achieved using:

a-1) Hazard data-collection and mapping
a-2) Vulnerability assessment
a-3) Risk assessment
Risk mitigation: risk mitigation methods are used to mitigate or eliminate the intensity of hazardous events. These approaches could reduce existing vulnerabilities using retrofitting or strengthening methods.
Risk transfer: risk transfer mechanisms could not mitigate the vulnerability of asset, but they could effectively reduce financial risk associated with natural disasters by ensuring that needed funds would be available when hazard occurs. Due to the unacceptable economic efficiency of these approaches, it is important to use all available options to mitigate the vulnerability of structures before using transferring risk methods. Some of main risk transfer approaches are as follows:
a-1) Market Insurance and Reinsurance
a-2) Budget self-insurance
a-3) Public asset coverage
Emergency preparedness: emergency preparedness used to Increase early responses in a more effective and faster way to saving lives and improving the recovery of communities after occurrence of an extreme event. This method includes providing shelters, using early warning systems, preparing evacuation plans.
According to Demeter (2005), available options in post-disaster phases maybe include 1) emergency response, (ii) rehabilitation and (iii) reconstruction of the structure.

2-2-RETROFITTING

2-2-1 Definition:

At first, some other terms which synonymously used instead of the retrofitting should be clarified. Repairing refers to a process that provides the same strength of structure before damage occurrence. On the other hands, strengthening is a method which provides higher level of strength than the original building. There is also another term called remodeling that related to reconstruction of some part of an existing structure.
According to the mentioned definition, retrofitting would be referring to defining the procedures which have done during strengthening, remodeling and repairing methods. Retrofitting activities have been widely used in order to improve seismic performance of RC structures.
There are two other standard terms related to retrofitting activities, rehabilitation and restoring. Rehabilitation consists of reconstruction of a damaged structure while restoring refers to the rehabilitation of a structure as a general term consists of repairing, remodeling, strengthening and rehabilitation activities (Macit 2002).

2-2-2 Background

2-2-2-1 Federal Emergency Management Agency (FEMA)

Federal Emergency Management Agency (FEMA) was published FEMA 273 and FEMA 274 as two guidelines for seismic rehabilitation of buildings. After that, FEMA 356 entitled of "Prestandard for Seismic Rehabilitation" were released based on FEMA 273 and 274. It was intended to be used as a relevant source for professional designs, code officials and building owners to undertake the seismic rehabilitation of structures.

2-2-2-2 Applied Technology Council

Evaluation and retrofit of concrete buildings (ATC-40) suggested seismic rehabilitation procedures in which, Alternative retrofitting approaches were categorized into two main groups consist of: a) technical strategies and b) management strategies. These mentioned categories would be investigated in the next (Çetinceli, 2005).

2-2-2-3 Technical Strategies

Technical strategies suggested some reliable methods for the seismic performance of the building. According to these strategies, influential fundamental factors in the lateral force-resisting system's responses are 1) mass of building, 2) stiffness, 3) damping, 4) configuration and 5) deformation capacity.

System completion, system strengthening, improving deformation capacity, and reducing earthquake loads are methods suggested by technical strategies.

System completion

This approach had been recommended for the structures which have walls, diaphragms, and frames. These kinds of structures behave as a lateral force-resisting system which has acceptable performance level with some local failures caused by a) insufficient chord and collector elements at diaphragms, b) Inadequate bearing length in precast elements and c) Inadequate anchorage or bracing

Therefore, using diaphragm chords drags, and collectors (for timber diaphragms), using steel-based connectors (for buildings that consist of precast elements) and bracing and anchoring the building are the general methods for system completion.

System strengthening

System strengthening and stiffening are the most common option for improving the seismic performance of RC structures. System strengthening increases total lateral force bearing capacity of the structure, and system stiffening will shift performance of the structure to more resistant levels. This aim could be achieved using shear walls

b-1) Shear walls:

One of the most suitable rehabilitation methods which increase strength and stiffness is using reinforced concrete (RC) shear walls in existing structures (Fig.2.3). Some researcher investigates the effect of using shear walls on the system, and they finally recommended to employ shear walls in order to prevent large deformations caused by seismic excitation (Ozkul et al. 2019, Fintel 1991, Satpute and Kulkarni 2013, Gorgulu and Taskin 2015). It must be noted that employing shear walls may cause some problems in architectural design phases.

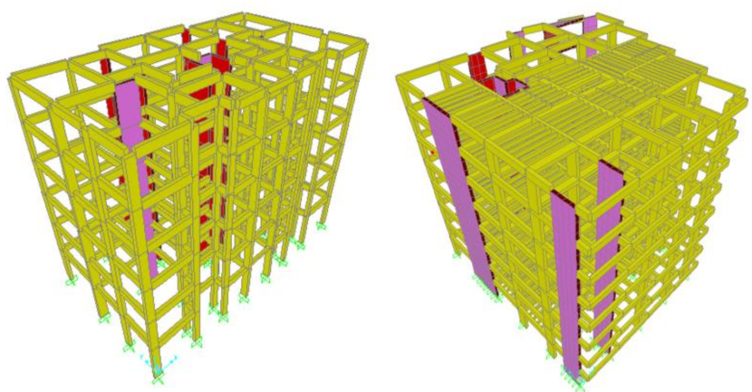


Figure. 2.3 Numerical model of using shear walls in a building (Ozkul et al. 2019)

According to the study conducted by Ozkun et al. (2019) using shear walls will have a considerable effect on the seismic performance of RC structures. Some other conclusions can draw from this study as follows:

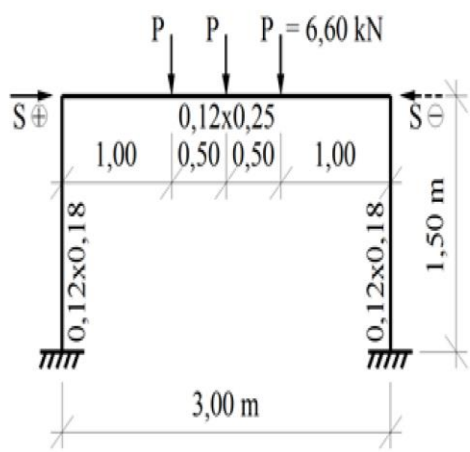
In a condition that hysteretic damping capacity and ductility capacity of shear walls are adequately enough, shear walls would have considerably support structure against seismic excitations, in other words, using adequately designed shear walls could decrease damage levels of structure even in condition with low ductile columns.
Shear walls with insufficient reinforcement, would not improve the seismic performance of RC structures. In other words, shear walls could not improve the seismic behavior of structure if their strength and ductility do not meet the code requirements.

b-2) Carbon Fiber Reinforced Polymer (CFRP)

In order to strengthen infill walls, Carbon Fiber Reinforced Polymer (CFRP) has been used in recent years. Using CFRP technique is easy to use, applicable fast and very popular in comparison to other methods in the rehabilitation of RC structures. It is also a very efficient method because it does not evacuation needed during rehabilitation. Many researchers have studied the effectiveness of these rehabilitation techniques on improving the seismic performance of RC structures. These rehabilitation techniques would effectively improve strength, stiffness, and capacity of energy dissipation in RC structures.

Issa and AbouJouadeh (2004) were conducted some experimental test in order to investigate the effect of using CFRP on the structural capacity of the beam. All the specimens represent three phases: pre-cracking, cracking to yield, and finally yield to crushing. The cracking phase was improved by the application of CFRP laminates. They concluded that using CFRP materials is one of the most powerful approaches for strengthening RC members of a structure. Strengthening of structural members using CFRP results increasing in load-bearing capacity and stiffness. Stiffness and rigidity of structural members were improved using the CFRP laminates, which prevent members crushing without pre-warning.

Dan et al. 2018 investigated the application of CFRP in the structural capacity of a frame which was subjected to vertical and horizontal loads as shown in Figure 2.4a and 2.4b. All the tests were conducted in force-controlled condition, first up to the service phase, yielding and finally failure stage.



a)

b)

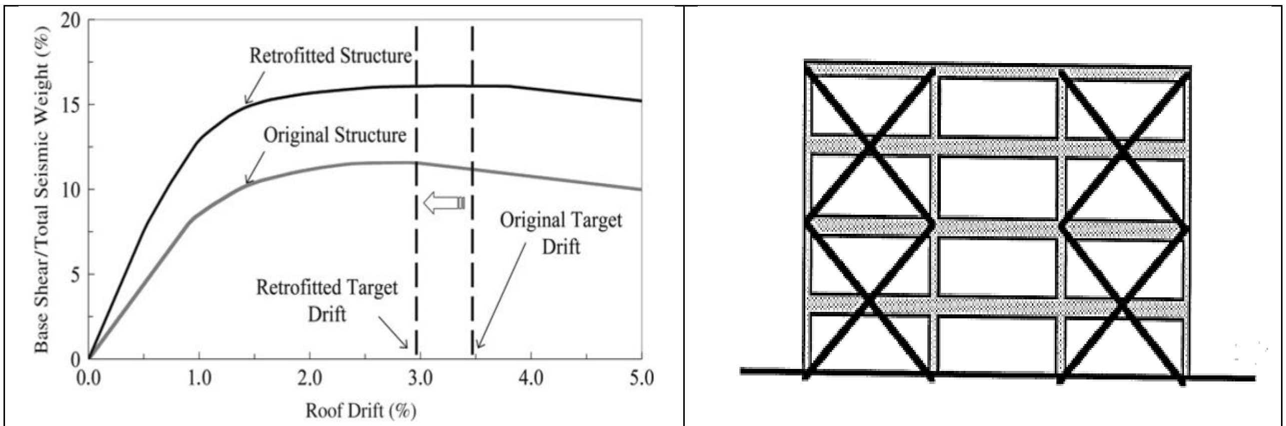
Figure. 2.4 a) RC frame and loading outline and b) RC frame (Dan et al. 2018)

Based on this research, some aspects of using CFRP strengthening methods were highly increased resistance and stiffness of RC frames. According to important technical and economic advantages of CFRP, the strengthening method using CFRP might be used for rehabilitation of various types of structures as shown by Constantin et al. (2018) and Lazar et al. (2018).

Results above indicate that the application of CFRP methods could increase the strength of RC frame and structural members and provides additional load-bearing capacity.

b-3) Braced frames

Another standard method for retrofitting RC structures is, bracing frames with steel. The approach above does not effective as equally as shear walls in increasing strength and stiffness but using this method does not result in increasing structure mass because shear walls are much heavier than braced frames. This would be helpful to reduce seismic forces on the system.
There are several options of braced frames (Fig. 2.5-b) which could be employed for seismic rehabilitation of RC structures. The most commonly used systems are consisting of concentrically braced frames (CBFs), knee-brace frames (KBFs), special concentrically braced frames (SCBFs), eccentrically-braced frames (EBFs), buckling-restrained braces (BRBFs) and mega-braces (MBps). There are also Macro-bracings frames (MBFs) which could be useful for strengthening of steel-framed structures (Di Sarno and Elnashai. 2009, Erdurmuş. 2005).
Commonly, in global modifications to the RC structures, the design demands on the existing structural components are considered as a lower level in comparison to their capacities (Fig. 2.5-a).



a) b)

Figure. 2.5 a) Characteristics of common approaches in retrofitting of structures. (Di Sarno and Elnashai, 2009) b) steel bracing (Badoux and Jirsa, 1990)

Di Sarno and Elnashai (2009) were studied the application of braced frames. They carried out the research through a 2D finite element (FE) program entitled DRAIN-2DX. They assessed using three configurations of bracing frames SCBF, BRBF, and MBF. The results of the numerical analyses illustrate that MBFs is the most cost-effective option. Reduction of structural drift in comparison with the original frame was about 70%. BRBFs are only slightly superior to the MBFs retrofitting system despite their higher weight. The total amount of structural steel which had been used in configurations with MBFs is 20% lower than in SCBFs that consequently will reduce construction cost.

b-4) Buttresses

Buttress plays as exterior support and in some cases can be decorative. Buttresses could be employed on the outside of a structure. Is an exterior structure built against the main structure to support it. Historically, this method had been used in order to strengthen building such as churches, but in recent decades they have been employed to support modern structures such RC building and dam. This method is applicable in such cases which occupancy of the case structure is necessary during the rehabilitation phase. Fig. 2.6 depicts some application of buttresses in building and dam structures.

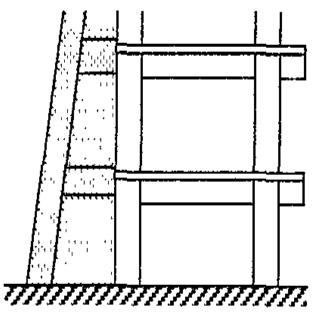
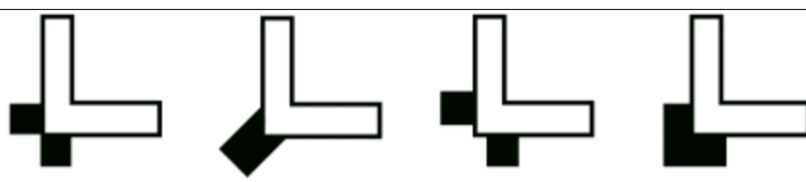
		
a)	b)	c)

Figure. 2.6 a) conceptual usage of buttress (Sugano, 1996) and application of buttresses in b) historical building and c) dam structure (https://www.designingbuildings.co.uk).

There are some common and applicable types of the buttresses for strengthening structure; 1) a clasping buttress is an L shape buttress that surrounding the corner, 2) an angled buttress in which two buttresses meet each other at the corner, 3) a setback buttress consists of two buttresses which are set back from the corner and a 4) diagonal buttress. Fig.2.7 represents these four mention types of buttresses.



a)	b)	c	d)

Figure. 2.7 a) an angled buttress b) a diagonal buttress c) a setback buttress and d) a clasping buttress (http://www.lookingatbuildings.org.uk) .

b-5) Moment resisting frames

Using moment resisting frames is another method for strengthening system which could improve the strength of the RC structure (Fig.2.8).

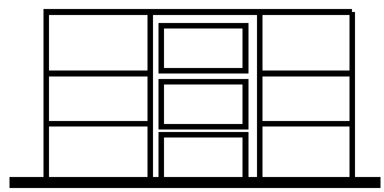


Figure. 2.8 using moment resistant frame in a building

b-6) Diaphragm strengthening

Marini et al. (2008) used Fiber-reinforced concrete floor diaphragms as a strengthening method in order to gather and transfer the horizontal loads to the shear resistant walls. Diaphragms can be modeled as beams and design parameter could be obtained using the capacity design criteria and to the chord and panel structure (Fig.2.9). Numerical modeling approach had been used in order to investigate the effects of using the diaphragm strengthening method on the behavior of a structure located in very seismic areas (Marini et al. 2008). Some of noticeable results of this study can be summarized as follows:

Using Fiber reinforced concrete could significantly reduce the diaphragm thickness.

In order to achieve a ductile flexural failure, fiber reinforced concrete (FRC) diaphragms could be used.

Fiber-reinforced concrete diaphragms could effectively improve seismic capacity of masonry heritage and modern reinforced concrete structures. Improving deformation capacity

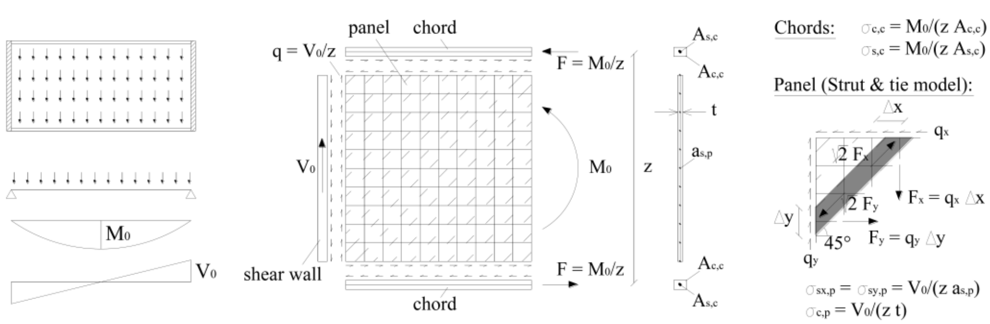


Figure. 2.9 Panel model and chord and for a standard diaphragm (Marini et al. (2008)

Most typical methods among this technique are column jacketing, strengthening column, and providing additional supports.

c-1) Column jacketing

Using column jacketing could enhance the deformation capacity of brittle columns; in other words, jacketing techniques are used in order to improve columns ductility. There some types of jacketing such as confining with steel plates, concrete jacketing and using fiber-reinforced plastic fabrics. It must be mentioned that proper attachment of the confinement plays an important role in the ineffectiveness of this technique.

Chalioris et al. (2014) used thin, reinforced self-compacting concrete (SCC) jackets to repair and to strengthen concrete members through experimental and analytical investigations (Fig.9). The experimental study comprises 20 tests which were designed to fail mostly in shear with no ductility. After initial loading until near failure phase, specimens were repaired with SCC jackets. Then tests were subsequently restarted in order to demonstrate improved strength and ductility of specimens.

The obtained results revealed that the application of the column jacketing would lead to full recovery of heavily damaged members and even causes significant improvement of strength and ductility. It must be mentioned that the efficacy of the repairing procedure (proper anchorage) directly controls the post-repair characteristics of the member (Chalioris et al. 2014). Longitudinal reinforcement bars could be anchored to the original column using a two-component epoxy resin.

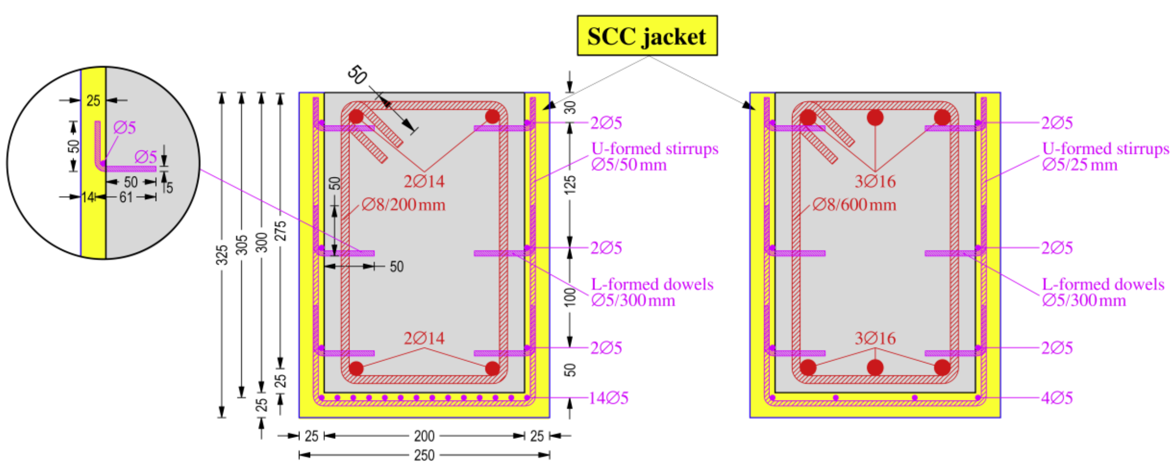


Figure. 2.10 Cross-section of specimens (Chalioris et al. 2014)

Ribeiro et al. (2018) Were evaluate the performance of an innovative confining hybrid FRP jacket for concrete columns. They performed a series of experimental test on cylindrical concrete specimens using hybrid and non-hybrid FRP jackets (Fig. 10). All the jackets were made using four commercially available fabrics: HM carbon (CHM), ST carbon (C), E-glass (G) and basalt (B) (Fig. 2.12).

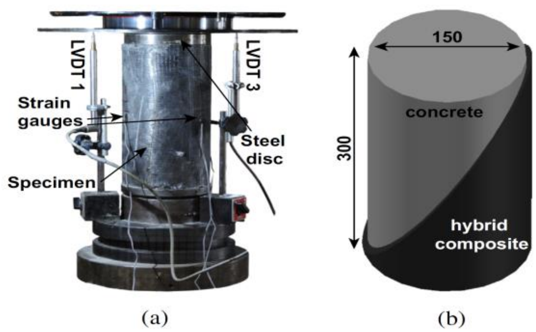


Figure. 2.11 Axial compressive test: (a) illustration of the test and (b) geometry of specimen (dimensions in mm).

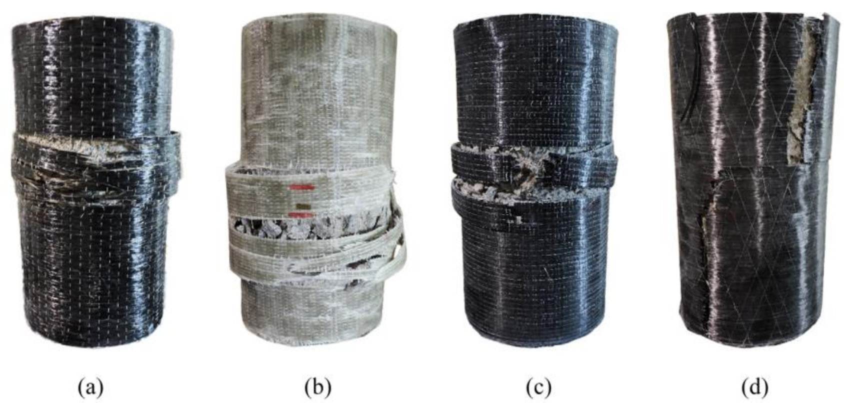


Figure. 2.12 Failure modes of non-hybrid FRP-confined concrete: (a) basalt; (b) glass; (c) ST carbon and (d) HM carbon (Ribeiro et al. 2018)

It was revealed from the results of study, that hybridization process could effectively contribute to maximizing the lateral strain efficiency of FRP jacketing (Ribeiro et al. 2018).

c-2) Column strengthening

Column strengthening would be useful for RC structures in which strong beam- weak column configurations appear. Mortazavi et al. (2003) presented a new strengthening technique for existing columns using expansive materials. The technique increased the capacity and ductility of the rested column. According to the obtained results, there is a possibility for controlling the applied pre-tension by controlling the amount of expansive material which has been used. Furthermore, it was confirmed that jacketing columns by pre-tensioned fiber-reinforced polymers could increase the load-bearing capacity up to 35%.

c-3) Enlargement

This method of strengthening involves placing additional overlay or a jacket into a structural member. Enlargement methods are used in order to improve the load-carrying capacity of columns, beams, walls, and slabs.

Shafaei et al. (2014) investigated the effect of using a practical seismic retrofitting method entitle of "joint enlargement using pre-stressed steel angles" of existing RC building. In this paper, the column-beam joint is enlarged using held in place (by high tensile strength bars) stiffened steel angles at the re-entrants corners of the column-beam joint in both above and below of the beam. The mentioned method is independently applicable to 3D-frames in each perpendicular direction (Fig. 2.13).

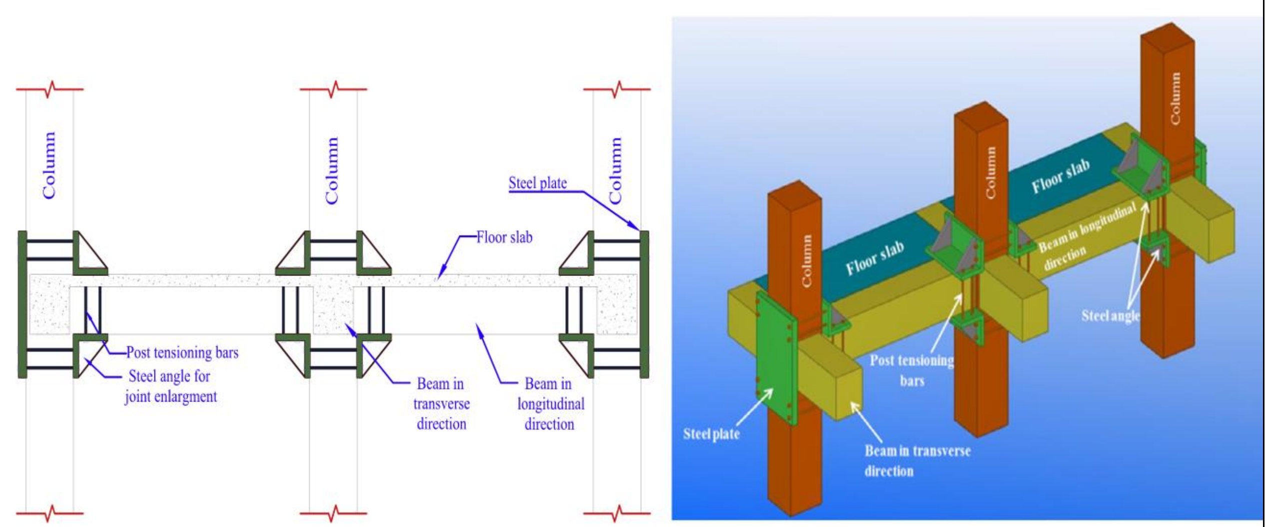


Figure. 2.13 Retrofitting an RC frame using joint enlargement using pre-stressed steel angles (Shafaei et al. 2014).

The design process of joint enlargement size should be done in order to improve the joint shear capacity by increasing effective joint area. The effective joint area is referring to the area which is resisting the shear loads within the joint. Fig. 2.14 shows the definition of effective joint area before and after using joint enlargement using pre-stressed steel angles (Shafaei et al. 2014).

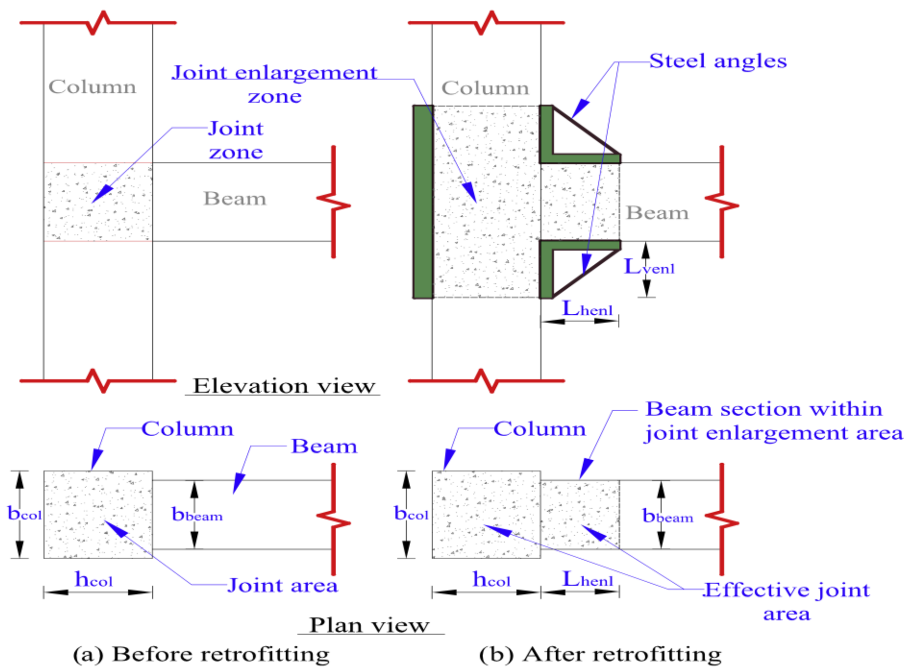


Figure. 2.14 Definition of the effective joint area before and after retrofitting (Shafaei et al. 2014).

The advantages of using this method with respect to the other standard retrofitting methods are easy and cost-effective installation of steel. Moreover, the size of the retrofitted beam-column joints marginally changes according to small size of the steel. Using joint enlargement using pre-stressed steel angles does not cause interruption to building services (Shafaei et al. 2014). The main results of this study are summarized as follows:

The proposed retrofitting method significantly postponed brittle failure by increasing the joint area and improving boundary between deformed bars and concrete.
Using this method resulted in plastic hinge relocation, away from the column to outside of the joint panel.
The proposed retrofitting method was shown to significantly enhance the seismic capacity of the joints, in terms of strength, stiffness, energy dissipation, and ductility capacity.

c-4) Local stress reductions

These procedures are consisting of:
- Demolishing stiff local members and respond lateral forces which could not handle
- Introducing joints between a column and adjacent architectural components.
-Reducing earthquake loads

The approach above requires some high technology, expensive protective systems. This method directly controls the demands of earthquake excitations while other techniques focusing on capacity improvement of structure (Erdurmuş, 2005). This method could be suitable for important building with high-value equipment or machinery and historical buildings.

d-1) Base isolation

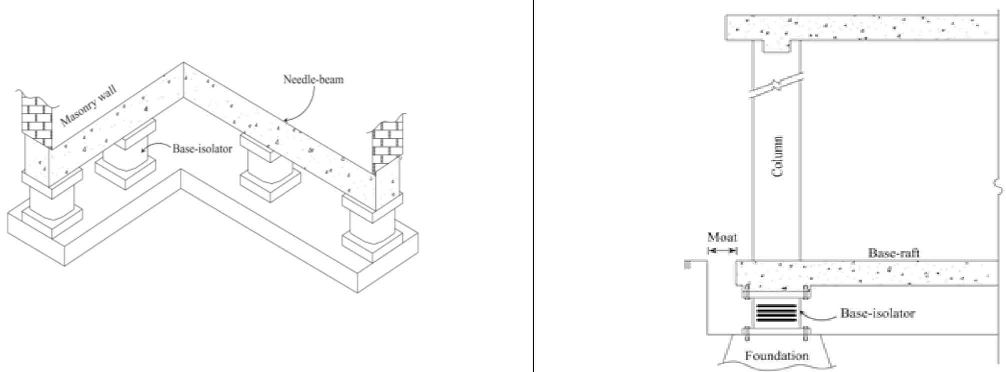
The techniques above, based on improving strength and ductility, are not always applicable for the seismic rehabilitation of existing structures. For heritage buildings which were designed without accounting for the seismic consideration, for complex structures, such as the old power plants, nuclear power plants, and industrial constructions, base isolation could be a suitable option.

The first Italian structure which had been retrofitted using base isolator was a 4-story reinforced concrete building with pile foundations. The isolators had been inserted by cutting pillars and walls at the foundation level. The pillars were reinforced, and a steel beam was inserted above the isolators in order to provide the required stiffness for correct transmission of the horizontal forces into the isolators (Fig. 2.15) (Clemente et al. 2012).

a) b)

Figure. 2.15 one of the building columns a) before the cutting phase b) after the installation of isolator (Clemente et al. 2012)

This method could be applicable in both masonry and framed structures, as shown in Fig. 2.14. In typical base isolation retrofitting work, the column must be cut using mechanical cutters, and the seismic base isolator will insert as shown in Fig. 2.16. It must be noted that placing the isolation layer in ground level would be more effective compared to the cases which the base isolators are placed on the first floor (Matsagar and Jangid, 2008).



a a

Figure. 2.16 Base isolator placement in a) load-bearing masonry structure b) framed structure (Matsagar and Jangid, 2008).

d-2) Energy dissipation systems

Using energy dissipation techniques has been considered for many years, and a rapid increase in application started in the mid-1990s. Reducing the energy dissipation demand on the structure is the reason for using an energy dissipation system which would reduce damages to the frame system.

Energy dissipation devices which have mostly been used for seismic protection of structures are consist of friction dampers (FD), solid viscoelastic dampers (VSD), viscoelastic dampers (VD), metallic dampers (MD) and viscous fluid dampers (VFD) (Symans et al. 2008).

Earliest applications of damping systems were employed to reduce deformations in tall buildings. For these cases, large amplitudes of oscillations which could be caused by either wind forces or seismic excitations can be very unpleasant to the occupants. Energy dissipation systems have been effectively used in order to reduce the amplitudes of vibration. Recent applications of the energy dissipation devices were employed for a wide variety of structures. Fig. 2.17 represents some applications of energy dissipation systems in different structures. Application of energy dissipation systems in Hotel Stockton, Stockton, Calif which is a non-ductile reinforced concrete structure was built in 1910. The renovation process had been started was included using 16 viscous fluid dampers and 4 viscoelastic fluid dampers (Fig. 2.17-a). The retrofitting procedure of Wallace F. Bennett Federal Building, Salt Lake City, Utah which is an eight-story RC building had to be completed with minimum disruption to the occupants. Therefore, a braced frame system in the exterior area of the structure was considered. The final design included 344 restrained buckling braces (Fig. 2.17-b) (Symans et al. 2008).

a) b)

Figure. 2.17 a) view of installed fluid viscoelastic damper b) view of building with installed buckling-restrained braces (Symans et al. 2008).

d-3) Mass reduction

Mass reduction technique could be a suitable retrofitting approach for some existing structures. In this method, by decreasing the mass of the system, the corresponding vibration period would be decreased which consequently reduces inertial forces. This method applies to an existing RC Structure through removing some heavy non-structural components such as; water tanks, storages, heavy equipment, and architectural features. The mass reduction may involve the process of removing one or more stories in the building (Fib, 2003).

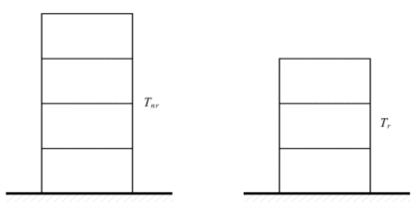


Figure. 2.18 Mass reduction technique (Oliveto and Marletta, 2005)

Another aspect of using mass reduction technique revealed that reducing vibration period of structure would lead to a higher demand on the system. According to Fig. 2.18 by removing a story in structure, fundamental period would decrease to T_r (Fig. 2.19), cause higher demand S_{ar}

(in pseudo-acceleration term). Thus, application of this method for increasing the seismic capacity of an RC structure could increase the seismic demand (Oliveto and Marletta, 2005).

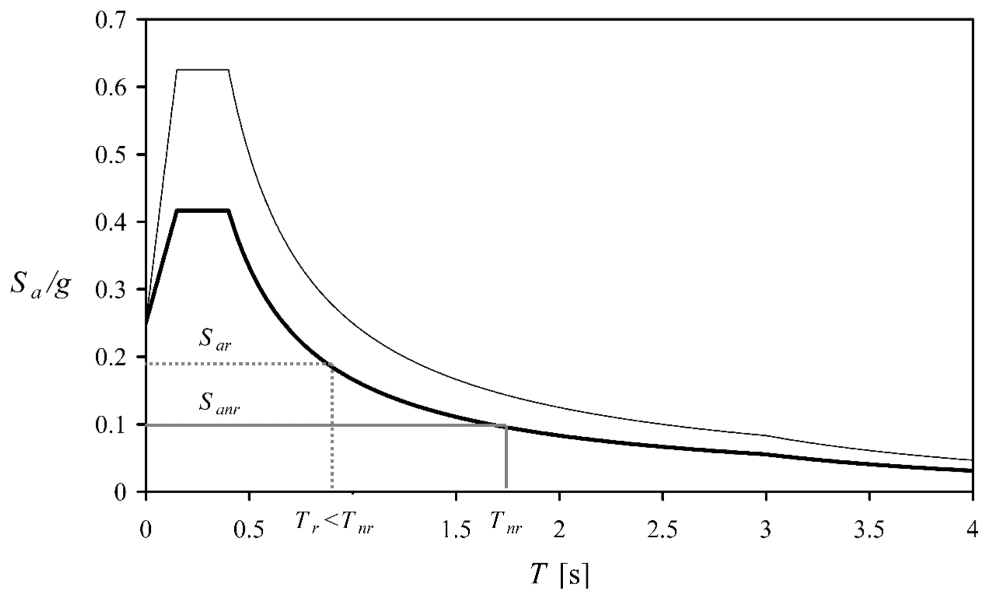


Figure. 2.19 Increase of the seismic demand following an increase of seismic resistance (Oliveto and Marletta, 2005)

2-3. ACI 546 recommendations for concrete repairing

ACI 546 provides guidelines for selecting and application of useful materials and methods for repairing and strengthening and protecting of deteriorated or damaged concrete structures in order to adapt a structure for a new application or overcoming construction or design deficiencies

A rehabilitation procedure commonly involves the process of removing damaged or deteriorated concrete. Since it is not easy to determine when all the damaged concrete has been removed or when too much has been removed, and it is recommended to continue the removal process until aggregate particles are being broken rather than removing from the cement matrix. It must be noted that removing the concrete using violent methods such as blasting would cause damage to the non-damaged concrete which is intended to remain.

Selecting applicable, economical and safe concrete removal techniques would that minimize damage to the left-over concrete. This selection directly affects the time duration that a structure must stay out of service for removal procedures. The mechanical characteristics of the concrete which supposed to be removed would provide important information required to choosing suitable method and estimation of concrete removal costs.

2-3-1 a) Classification of concrete removal techniques

According to how the removing process acts on the damaged concrete, concrete removal techniques would be classified. These classes consist of blasting, cutting, impacting, milling, pre-splitting, and abrading method.

a-1) Blasting methods

Explosive blasting is the most cost-efficient technique for removing large quantities of concrete. This method consists of 1) drilling boreholes, 2) placing an explosive in each borehole and 3) detonating the explosive material (Fig. 2.20) represents important parts of drilling and blasting process). Control blasting would be useful in order to control and minimize damages to the remained concrete material after blasting. For example, cushion blasting method involves drilling a series of boreholes, loading each hole with explosive materials, cushioning the charges by stemming each hole completely and finally detonating the explosive. Also blasting machines and electrical blasting-cap which employ suitable timing sequences are used for blast controlling.

The proper selection of charge weight borehole diameter and borehole spacing depends on 1) the location of the structure, 2) acceptable level of vibration and 3) the quantity and quality of concrete which must be removed.

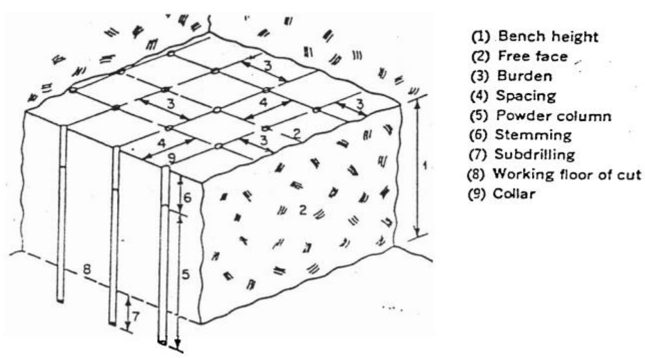


Figure. 2.20 important parts of drilling and blasting process (LaGuardia, 1980).

a-2) Cutting methods

Cutting methods usually use mechanical sawing, intense heat, or water jets to cut and remove the specific perimeter around the concrete sections. The cutting techniques are including diamond saw cutting, thermal lance, powder torch, powder lance, electric-arc equipment, and water jets.

a-2-1) High-pressure water jet

A high-pressure water jet as one of cutting methods uses a jet of water which is driven with high velocities and consequently high pressures from 69 to 310 MPa (Fig.2.21-a). Nowadays, there are some commercially available types of water jet systems which are being used. Two of the most reliable types of high-pressure water jet are ultra-high-pressure jet and cavitating jet (Fig.2.21-b). Over the last years, water jet systems have been greatly improved in terms of efficiency and productivity.

a) b)

Figure. 2.21 application of a) ultra-high-pressure jet and b) cavitating jet (www.hppumpservices.co.uk) for concrete removing

a-2-2) Saw

Carbide or diamond saws are available in various sizes from very small to very large up to 1.3m (Fig.2.22-a). A diamond saw could be applied with other methods to improve crack control by cutting specific area.

a-2-3) Diamond wire cutting

Diamond wire cutting is accomplished with a wire which is wrapped around the concrete block (Fig.2.22-b). This method could be applied for any concrete block size, but, the main restriction would be the power of source.

	
a)	b)

Figure. 2.22 application of a) Saw (www.wilderdiamond.com) and b) Diamond wire cutting (www.tecnotaglisrl.eu) for concrete removing

a-2-4) Mechanical shearing

The mechanical shearing approach uses hydraulic jaws in order to remove reinforced concrete. Starting the removing process from free edges would be the main restriction of this approach.

Commercially available types of this approach consist of; a) Stitch drilling, b) Thermal cutting, c) Impacting method, d) Milling methods e) Hydro-demolition, f) Prospecting methods g) Abrading methods

2-3-2 b) Surface preparation

Surface preparation is considered as one of the important steps in the rehabilitation procedure of a concrete structure. Ensuring the expected behavior of structure needs repair procedure which includes preparation of the reinforcing steel in order to obtain a suitable bond with the replacement concrete. Most of the mentioned methods in a cutting category could also be applicable for surface preparation. Standard methods for surface preparation are summarized as follows:

b-1) Acid etching.

For a long time in order to remove dirt and laitance, acid etching has been used. According to ACI 503R application of acid, etching is not recommended while ACI 515.1R recommends the application of acid in only conditions which no other option of surface preparation could be employed.

b-2) Chemical cleaning.

Using certain coating, it might be possible to use chemical cleaning such as trisodium phosphate. It should be mentioned that the used cleaning agent should be removed after the contaminating material is removed.

b-3) Mechanical preparation

This technique refers to mechanically removing layers of surface concrete Using some equipment such as (breakers, scabblers), grinders, and scarifier. This method could be applied to various types of surfaces, depending on the chosen equipment.

b-4) Abrasive preparation.

This technique consists of removing thin layers of surface concrete using abrasive equipment such as sandblasters, shot-blasters, or high-pressure water blasters.

2-3-3 C) Repair materials

There are some materials which could be applicable for repairing or rehabilitating of concrete structures. These materials will be categorized entitled "Repair materials" which are consist of the following items;

C-1) Conventional concrete

Conventional concrete which is a combination of portland cement, aggregates, and water could be used as a repairing material. There are some admixtures which are frequently used in order to entrain air, accelerate hydration, improve workability, reduce mixing water requirements and increase strength of the concrete.

C-2) Conventional mortar

Conventional mortar is a mixture of portland cement, fine aggregate, and water. Water-reducing admixtures, expansive agents, and other available admixtures are often used with conventional mortar in order to minimize shrinkage. The main advantage of using conventional mortar Compare to conventional concrete is the applicability of placing in thinner sections.

C-3) Dry pack

Dry pack mortar may consist of cement, parts sand and only enough water so the mortar will stick together. Because of the low initial water content of the dry pack mortar curing process is critical.

It must be noted that most of the mentioned techniques from repairing and strengthening to cutting and surface preparation methods are not restricted to any specific structural elements. A large portion of this methods applies to beams, columns, and slabs unless there would be some case dependent exotic limitations. Therefore, practical guidelines and codes, generally do not restrict these methods for a specific structural element.

Chapter 3: Research methodology

3.1. Introduction

In this chapter, the employed method for the decision-making process will be fully described. An introduction to multi-objective optimization and weighted sum method is further presented. All the variables and functions (solution vectors, objective functions, and constraints) due to concrete retrofit methods are then introduced. The reader will be able to follow the procedure and make their configurations if needed.

3.2. Multi-objective optimization

In practice, many engineering problems can be solved with more than one specific solution, and there are always multiple objectives to be satisfied. Such as low cost, durability and being environmentally friendly. These objectives sometimes conflict with each other making a solution which satisfies one objective dissatisfying to the other. For example, constructing a building with less energy consumption could end up more costly or employing a cheaper method could be damaging to the environment. Finding a proper solution to meet all criteria and somehow satisfy all objectives to a certain degree has always been a major issue for decision-makers (DMs). The process of finding proper solutions due to the objectives and constraints is called multi-objective optimization (Konak et al. 2006).

Multi-objective optimization is an excellent way to search in a set of different solutions, each of which satisfies each objective to a certain degree. Since the number of possible solutions in an engineering project can be dramatically large, as the number of one set of solutions can be multiplied by the other's and objectives can be somehow sophisticated, using a method to optimize and find the best-suited solutions is essential.

There are two general approaches to multi-objective optimization. The first one is to reduce the multi-objective optimization problem into a single-objective problem. To do this, each objective function should be assigned a proper weight by the decision-maker due to its importance in the current project. These weights could be different from one project to another (Schaffer, 1985). The key point is that the decision-maker should be fully aware of the situations governing the decision-making process and should be well qualified. It might be even better if a group of decision-makers attains the weight assigning process. On the other hand different set of assigned weights could be examined to make the best decision possible.

The second approach is to provide a set of optimized solutions so that the decision-maker could look for suited solutions in a smaller group. This set is usually shown in an n-dimensional frontier called Pareto front, in which "n" is the number of objectives. If the objectives are to be minimized the set is likely to be a convex surface. Each point on the surface or so-called Pareto front is an optimum solution. Moving from one point to the other on this surface to make the situations better for one objective will be accompanied with certain amount of sacrifice to at least one objective. The decision-maker will be able to decide better to choose their proper solution(Corne, 2000).

An example of Pareto front for a two-objective problem, if the objectives are to be minimized, as shown in figure 3.1.

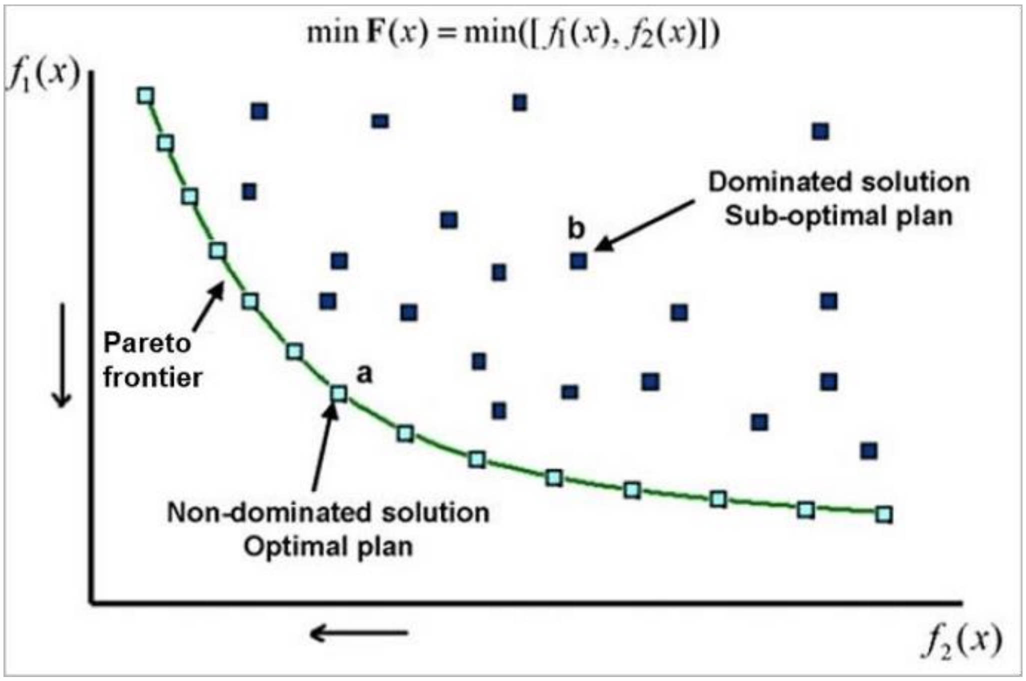


Figure 3.1: an example of Pareto front for a two objective optimization problem(Somma, 2016)

As said above, moving on the Pareto surface can make the solution better in respect to one objective while worsening to the other. This is a perfect tool for decision-makers to evaluate each solution on the front and be aware of the trade-offs to make a good choice.

There are two general categories of solutions: dominated and non-dominated. Dominated solutions are the ones in which there exist solutions that are better in at least one objective without being worse in any other. These solutions are plotted above the Pareto front. Non-dominated solutions, on the other hand are solutions in which there exists no other solution better in one objective without being worse in another(Knowles, 2000).

In this research, the optimum solution will be decided by the weighted sum method. Then the Pareto front will be drawn in order to visualize and make a better understanding of decision-making process.

A multi-objective optimization problem contains 3 main sets of vectors:

1. Solution vectors

2. Objective vectors or fitness functions

3. Constraint vectors

Solution vectors belong to an area in which the decision-maker looks for the proper answer for the given problem.

Each problem has certain objectives with different degree of importance. These are shown with fitness functions which are to be minimized. The variables that so-called fitness functions are solution vectors. The optimization methods goal is to find the solution vectors which result the smallest value for fitness functions.

In many engineering problems, there exist some constraints, such as limited budget or environmental concerns. These constraints are applied to the optimization problem by constraint vectors. If a variable which is a solution vector does not pass one of those constraints, it should be omitted from the process.

Each of those three sets of vectors will be further introduced.

3.3. Solution vectors

For an engineering problem, there always exist multiple numbers of solutions along with specific advantages and disadvantages. Concrete retrofitting is not an exception.

There are 3 main phases in repairing a damaged concrete part: Removal of the damaged part, surface preparation and placing the new material. As a concrete section consists of two main materials known as reinforcing and coating materials, the third phase divides into two sub-phases. For each phase, there exist different methods and materials which are introduced in the following section.

3.3.1. Concrete removal methods

3.3.1.1. Blasting with expansive agents

There are several expansive mediums available in the market. The one that is used in this research will be Dexpan expansive demolition grout. Dexpan is a non-explosive blasting agent, a powder with an eighteen thousand psi expansive pressure. The instruction is to first mix up with water and then put it in any place that must be removed. The price for a 44 lb. box is 99 US$. The procedure also includes drilling, which adds up certain price to the whole method.

The average salary for construction labor is 14.87 US$/h in United States of America. It increases with the hardness of the job and the specific skill required for the job.

The average pay for a driller is 20.56 US$/h.

For a one ft^2 of concrete removal, at least one lb. of Dexpan expansive demolition grout and 10 minutes of a drilling machine work and a simple worker will be needed. This makes the cost for this procedure about 8.16 US$/$ft^2$.

The amount of noise this procedure makes is only caused by drilling, which can make a noise of an average of 100 dB. The vibration made by drilling is usually around 100 Hz. This method emits a very low amount of dust and heat. The wastewater quantity produced would be none and debris would have a relatively large size. Blasting with expansive agents is considered as a simple method and does not require highly skilled labors (www.dexpan.com 2019).

3.3.1.2. Cutting with a high pressure water jet

The price for an abrasive water jet cutting is about 33 US$/h. This job also requires a worker to move the pieces. It makes the total cost for this procedure about 7.48 US$ if it takes 10 minutes.

The amount of noise made by this procedure is around 85 dB. The vibration made by this process is about an average of 110 Hz. This method does not emit any dust or heat. The wastewater quantity produced would be very high, and debris would have a very large size. Cutting with a high-pressure water jet requires skilled labor, so it is categorized as a very sophisticated method (https://wardjet.com 2019).

3.3.1.3. Cutting with a diamond saw

The price for a diamond saw cutting is about 30 US$/h. This job also requires a worker to move the pieces. It makes the total cost for this procedure, about 6.25 US$/h if it takes 10 minutes.

The amount of noise made by this procedure is around 105 dB. The vibration made by this process is about an average of 90 Hz. This method emits a high amount of dust and a moderate amount of heat. The wastewater quantity produced would be low, and debris would have a large size. Cutting with diamond saw is has a moderate degree of simplicity. It does not require any highly skilled labor though they should have some specialties in using the related equipment (www.payscale.com 2019).

3.3.1.4. Diamond wire cutting

The price for a diamond wire cutting service is about 35 US$/h. This job also requires a worker to move the pieces. It makes the total cost for this procedure about 8.31 US$ if it takes 10 minutes.

The amount of noise made by this procedure is around 100 dB. The vibration made by this process is about an average of 95 Hz. This method emits a moderate amount of dust and heat. The wastewater quantity would also be moderate. Debris will be very large in size. Diamond wire cutting is a very complicated method and requires highly skilled labors (www.indeed.com 2019).

3.3.1.5. Mechanical shearing

The price for a mechanical shearing machine service is about an average of 33.5 US$/h. This job also requires a worker to move the pieces. It makes the total cost for this procedure about 8.06 US$ if it takes 10 minutes.

The average amount of noise made by this procedure is around 90 dB. The vibration made by this process is about an average of 102 Hz. This method emits a moderate amount of dust and heat. The wastewater quantity would be moderate, and debris will have a very large size. Mechanical shearing is somehow a sophisticated method and requires labors with a good degree of skills (www.glassdoor.com 2019).

3.3.1.6. Stitch drilling

The price for stitch drilling is about 20.56 US$/h. This job also requires a worker to move the pieces. The procedure takes a bit more time than the usual cutting methods. It makes the total cost for this procedure about 8.86 US$ if it takes 15 minutes.

The average amount of noise made by this procedure is around 87 dB. The vibration made by this process is about an average of 100 Hz. This method emits a low amount of dust and a moderate amount of heat. Debris will have a large size. Wastewater quantity will need below. Stitch drilling is classified as a sophisticated method (www.payscale.com 2019).

3.3.1.7. Thermal cutting

The price of thermal cutting is about 26.3 US$/h. This job also requires a worker to move the pieces. It makes the total cost for this procedure about 6.86 US$ if it takes 10 minutes.

The average amount of noise made by this procedure is around 60 dB. This process does not produce any vibration. This method emits a very low amount of dust and a very high amount of heat. Wastewater quantity will need below. There might be some water used too cool down the concrete. Debris will have a very large size. Thermal cutting is considered as a sophisticated method not only because of the equipment being used but also because of the precautions that should be followed (www.payscale.com 2019).

Figure. 3.2 Thermal cutting (www.kandi.co.in 2019)

Figure. 3.3 Hand-held breaker (www.bunnings.com.au 2019)

3.3.1.8. Hand-held breakers

It is the simplest way to remove concrete. It only takes one worker to break the pieces and move them. The average pay for such worker is about 30 US$/h. The total cost will be 5 US$ if the whole procedure takes 10 minutes.

The average amount of noise made by this procedure is around 105 dB. The vibration made by this process is about an average of 200 Hz. This method emits a high amount of dust and a very low amount of heat. Wastewater quantity will be none. Debris will have a large size. Removing concrete by hand-held breakers is considered as a very simple method (www.glassdoor.com).

3.3.1.9. Boom mounted breakers

The price for boom mounted breaking procedure is about an average of 22 US$/h. This job also requires a worker to move the pieces. It makes the total cost for this procedure about 6.14 US$ if it takes 10 minutes.

The average amount of noise made by this procedure is around 108 dB. The vibration made by this process is about an average of 190 Hz. This method emits a high amount of dust and a very low amount of heat. Debris will be large. Wastewater quantity produced in this procedure will be very low. Operating boom-mounted breakers requires skilled labors, so it is a complicated method (http://neuvoo.ca 2019).

Figure. 3.4 Boom mounted breaker (http://mcquaidengineering.com 2019).

3.3.1.10. Scabblers

The price for scabblers is about an average of 20 US$/h. This job also requires a worker to move the pieces. The procedure is more time consuming than the usual. It makes the total cost for this procedure about 8.71 US$ if it takes 15 minutes.

The average amount of noise made by this procedure is around 97 dB. The vibration made by this process is about an average of 120 Hz. The amount of dust and heat produced by this method is high. There will be a very low degree of wastewater quantity. Some water may be used to wash up the concrete after the procedure. Debris will have relatively very small size. Using

3.3.1.11. Scarifiers

The price for scarifiers is about an average of 24.31 US$/h. This job also requires a worker to move the pieces. The procedure is more time consuming than the usual. It makes the total cost for this procedure about 6.53 US$ if it takes 10 minutes.

The average amount of noise made by this procedure is around 100 dB. The vibration made by this process is about an average of 130 Hz. The amount of dust and heat produced by this method is high. There will be a low degree of wastewater quantity. Some water may be used to wash up the concrete after the procedure. Debris will have relatively very small size. Using scarifiers is considered as a sophisticated method (https://www.mymajors.com 2019).

3.3.1.12. Hydro demolition

It is a much faster way to remove a damaged part. Hydro demolition usually takes about one or two minutes to remove a square foot of concrete. The hourly cost is around 200 US$ which makes this procedure about 6.67 US$/ft^2.

The amount of noise made by this procedure is around 88 dB. The vibration made by this process is about an average of 120 Hz. This method does not emit any dust or heat. The wastewater quantity produced would be very high, and debris would have a very small size. Hydro demolition requires skilled labor, so it is categorized as a sophisticated method (www.payscale.com 2019).

3.3.1.13. Hydraulic splitter

This method is also a rapid procedure that takes a lot less time than the previous methods discussed. Hydraulic splitter usually takes about four minutes to remove a square foot of concrete. The hourly cost is around 180 US$ which makes this procedure about 12 US$/ft^2. This procedure does not require any further surface preparation.

The amount of noise made by this procedure is around 85 dB. The vibration made by this process is about an average of 110 Hz. This method does not emit any dust or heat. The wastewater quantity produced would be very high, and debris would have an enormous size. Operating hydraulic splitter requires skilled labor, so it is categorized as a very sophisticated method.

3.3.1.14. Sandblasting

An average sandblasting procedure usually costs around 52.5 US$/h. This process is somehow time-consuming in larger pieces to be removed. For one ft^2 section it takes about 15 minutes to complete the procedure, but it does not require any further surface preparation. The cost for a square feet section will be 13.12 US$.

The amount of noise made by this procedure is around 110 dB. The vibration made by this process is about an average of 70 Hz. This method emits a very high amount of dust and a high amount of heat. Debris will have a minimum size. Wastewater will have a high amount as the water will be used to wash up the plant of all the blasting materials. Sandblasting is classified as a sophisticated method (www.payscale.com 2019).

3.3.1.15. Shot blasting

The price for shot blasting method highly depends on the blasting media. For a usual shot blasting procedure the hourly cost will be around 65 US$/h. This process is time-consuming since a square feet concrete section usually takes about 15 minutes to be removed, but there will be no need for any further surface preparation. The cost will be 16.25 US$/ft^2.

The amount of noise made by this procedure is around 115 dB. The vibration made by this process is about an average of 73 Hz. This method emits a very high amount of dust and a high amount of heat. Debris will have a minimum size. Wastewater will have a high amount as the water will be used to wash up the plant of all the blasting materials. Shot blasting is classified as a sophisticated method (www.glassdoor.com 2019).

3.3.1.16. High-pressure water blasting

High-pressure water blasting is somehow like other methods relying on water pressure. The cost of this method will be around 150 US$/h. The process usually takes 5 minutes, so the cost per square feet will be 12.5 US$.

The amount of noise made by this procedure is around 90 dB. The vibration made by this process is about an average of 128 Hz. This method does not emit any dust or heat. The wastewater quantity produced would be very high, and debris would have a minimum size. High-pressure water blasting requires skilled labor, so it is categorized as a very sophisticated method (www.ziprecruiter.com 2019).

3.3.2. Surface preparation methods

3.3.2.1. Chemical cleaning

It is cleaning a concrete surface in order to get it ready for the further construction and replacement of damaged part by chemicals costs around 9.28 US$/ft^2. It makes no sound or vibration and emits no amount of heat and dust. However, the wastewater quantity will be very high as in some cases it can be hazardous to the environment. Chemical cleaning is classified as a sophisticated method as it requires precaution while operating. This procedure takes about 5 minutes for one ft^2 (www.costwater.com 2019).

3.3.2.2. Acid etching

This method usually costs around 12.5 US$/ft^2. It does not emit any dust but low heat. It also does not produce any sound or vibration. Wastewater quantity will be high as it takes no significant amount of acid to etch the concrete surface, but the process may require using some water to weaken the acid and reduce its PH after preparing the concrete and let go of the remaining. Acid etching requires highly skilled labor so it is considered as a very sophisticated method since special precautions should be followed and care should be taken. This procedure takes about 4 minutes for one ft^2 (www.precisionmicro.com 2019).

3.3.2.3. Scabblers

Scabblers have been discussed in the previous section on removal methods. The procedure will be the same, but the time needed to do the procedure will be no more than 2 minutes for one ft^2. So the price will be 0.67 US$ for preparing one ft^2 of concrete surface (www.comparably.com 2019).

3.3.2.4. Scarifiers

This method has also been talked about in the previous section on removal methods. The time needed for this method will not be any more than 1 minute. So the price will be around 0.4 US$/$ft^2$ (www.mymajors.com 2019).

3.3.2.5. Grinder

The average pay for a grinder operator is around 19 US$/h. Preparing a concrete surface in this method will only take 1.5 minutes so that the cost will be 0.48 US$/$ft^2$. This method emits a moderate amount of dust and a low amount of heat. There will be 110 dB of noise and 100 Hz of vibration while using a grinder. The wastewater quantity will be very low. This procedure is considered as a moderate method in the sense of simplicity (www.indeed.com 2019).

Figure. 3.5 Grinder (www.forconstructionpros.com)

3.3.2.6. Sandblasting

This method has been talked about in the previous section on removal methods. It will take about a minute to prepare the surface by sandblasting. So the cost will be about 0.87 US$/$ft^2$ (www.payscale.com)

3.3.2.7. Shot blasting

This method has been talked about in the previous section on removal methods. It will take about a minute to prepare the surface by shot blasting. So the cost will be about 1.08 US$/ft^2 .

3.3.3. Coating materials

3.3.3.1. Conventional concrete

The cost to install a conventional concrete coating includes the pay for professional labor and the cost of materials being used. The average pay for a professional worker to install a conventional concrete coating is an average of 5.5 US$/ft^{2,} and the cost of conventional concrete in a square foot is about 1.5 US$. That makes the process 7 US$/ft^2 (www.studioavigopalumbo.it 2019).

3.3.3.2. Conventional mortar

It is a cheaper option for coating materials. The price of the labor will be 5 US$, and materials will be 0.5 US$/ft^2. It sums up to 5.5 US$/ft^2.

3.3.3.3. Dry-pack mortar

The price for installing a dry-pack mortar coating is an average of 6.85 US$/ft^2. (www.homewyse.com 2019).

3.3.3.4. Proprietary repair mortar

The cost for material is an average of 2.5 US$/ft^{2,} and the pay for labor is 5.5 US$ for one ft^2 installation. So it sums up to 8 US$/ft^2 (www.stetsons.com 2019).

3.3.3.5. Ferrocement

In this method, the pay for the labor will be as same as for conventional concrete which is 5.5 US$/ft^2. The cost of the material will be 1.76 US$/ft^2. That makes the whole process cost 7.26 US$/ft^2.

3.3.3.6. Fiber-reinforced concrete

Fiber-reinforced concrete is a material containing discrete and randomly oriented fibers resulting in higher bond and integrity in the structure of concrete.

In this method, the pay for the labor will be as same as for conventional concrete which is 5.5 US$/ft^2. The cost of the material will be 2.93 US$/ft^2. That makes the whole process cost 8.43 US$/ft^2 (https://abcpolymerindustries.com).

3.3.3.7. Magnesium phosphate concrete

Magnesium phosphate concrete is a cementitious material based on magnesium phosphate components. It has higher bond stress and lower shrinkage rate than conventional concrete.

In this method also the pay for the labor will be the same as for conventional concrete which is 5.5 US$/ft^2. The cost of the material will be 1.89 US$/ft^2. That makes the whole process cost 7.39 US$/ft^2 (www.hindawi.com 2019).

3.3.3.8. Preplaced aggregate concrete

Preplaced aggregate concrete is usually used where the use of conventional concrete is not easily applicable. It has a low shrinkage rate and is suitable for situations like dense reinforcement or underwater conditions.

3.3.3.9. Rapid setting cement concrete

The price for applying rapid setting cement is fairly the conventional concrete except the material is about twice as expensive, which makes the whole method cost 8.5 US$/ft^2. The benefit of this method is that the repair process could be done faster, but it is more expensive and has higher shrinkage rate and coefficient of thermal expansion than of conventional concrete (www.homedepot.com).

3.3.3.10. Shrinkage compensating concrete

Shrinkage compensating concrete is made by expansive cement or expansive additives. It is suitable for situations containing micro-cracks or places conditions requiring higher bond stress.

The price of this method is about 8.35 US$/ft^2 (www.concreteconstruction.net 2019).

3.3.3.11. Silica fume concrete

Concretes with silica fume additives have lower drying shrinkage, higher strength, lower water permeability, and lower coefficient of thermal expansion.

The price of this method is about 9.2 US$/ft^2 (www.engr.psu.edu 2019).

3.3.3.12. Polymer concrete

Polymer concrete is a type of concrete mixed up with polymer epoxies resulting in higher strength and durability.

3.3.4. Reinforcement materials

3.3.4.1. Galvanized reinforcement

This is a 1.12 US$/lb. In the given beam section, about 6.7 lb. of reinforcement steel bar is being used which makes the price around 7.5 US$/ft^2 (www.precisionsteel.com 2019).

3.3.4.2. Stainless steel reinforcement

This material costs 0.64 US$/lb. For a square foot of the given beam, 6.7 lb. of reinforcement steel bar must be used which makes the price 4.29 US$/ft^2 (https://cmcmmi.com 2019).

3.3.4.3. Stainless steel clad reinforcement

Stainless steel clad is a kind of steel made in a special metallurgical process resulting in higher strength and less corrosion capability. The cost of installed stainless steel clad reinforcement is approximately 1 US$/lb., which makes it 6.7 US$/ft^2 (www.nxinfrastructure.com 2019).

3.3.4.4. Fiber-reinforced polymer

Fiber-reinforced polymer or FRP is stronger yet more fragile material with high durability and resistance to corrosion. The cost is 8 US$/ft^2

3.3.5. Mathematical presentation

Solution vector is introduced to the computer program as a function of four variables. Each variable defines one of the solutions from the above categories.

Solution vectors are identified as follows:

a_i , b_j , c_k , d_l

"a" Introduces solutions from the first category. "i" is a counter between one and sixteen. "b" Introduces solutions from the second category. "j" is a counter between one and seven. "c"

Introduces solutions from the third category. "k" is a counter between one and twelve. "d" Introduces solutions from the fourth category. "l" is a counter between one and four. The values for a, b, c and d can only be either one or zero. The number of possible solutions is $16 \times 7 \times 12 \times 4 = 5376$.

$$a_m = \begin{cases} 1 & if\ method\ "i = m"\ is\ selected \\ 0 & otherwise \end{cases}$$

$$b_n = \begin{cases} 1 & if\ method\ "j = n"\ is\ selected \\ 0 & otherwise \end{cases}$$

$$c_o = \begin{cases} 1 & if\ method\ "k = o"\ is\ selected \\ 0 & otherwise \end{cases}$$

$$d_p = \begin{cases} 1 & if\ method\ "l = p"\ is\ selected \\ 0 & otherwise \end{cases}$$

3.4. Objective functions

Objective functions define the objectives of the problem in numerical order. In the present research, objectives are price, needed time to operate the process and durability. Each of them can have a certain degree of importance in a different project.

As the three mentioned objectives have different units and nature, in order to sum them up all together in a single weighted function, they should be normalized. The method employed to normalize an objective is described as follows(Murata, 1995).

$$Normalized\ objective = \frac{current\ value - minimum\ value}{maximum\ value - minimum\ value}$$

Price is one of the most important features of any method applied. It is always an objective for any project as the assigned budget and resources are limited. Any of the discussed methods in the solution area has a specific price value. The objective function for price is defined as follows:

$$P = \sum_{i=1}^{18} \sum_{j=1}^{8} \sum_{k=1}^{17} \sum_{l=1}^{4} (P_i^1 a_i \times P_j^2 b_j \times P_k^3 c_k \times P_l^4 d_l)$$

P_i^1 is the normalized price of method i in the first category of solution vectors, P_j^2 is the normalized price of method j in the second category of solution vectors, P_k^3 is the normalized price of method k in the third category of solution vectors and P_l^4 is the normalized price of method l in the fourth category of solution vectors.

The other objective is durability. Durability is the amount time that the repaired part is expected to serves appropriately and it is different for one method to another. In the same order as for the price objective, the function for durability is as follows:

$$D = \sum_{i=1}^{18}\sum_{j=1}^{8}\sum_{k=1}^{17}\sum_{l=1}^{4}(D_i^1 a_i \times D_j^2 b_j \times D_k^3 c_k \times D_l^4 d_l)$$

D_i^1 is the normalized durability of method i in the first category of solution vectors, D_j^2 is the normalized durability of method j in the second category of solution vectors, D_k^3 is the normalized durability of method k in the third category of solution vectors and D_l^4 is the normalized durability of method l in the fourth category of solution vectors.

The values of durability are originally qualitative due to each process. It depends on the potential of microcracking in removal method and quality of coating and reinforcing materials. Durability can have either five descriptions of very low, low, moderate, high and very high. In order to solve the problem in a mathematical order these descriptions need to be quantified. So the values of 0.2, 0.4, 0.6, 0.8 and 1 are assigned to durability representing very high, high, moderate, low and very low disabilities respectively.

The last objective discussed is time. It is the amount of time needed to finish a process for removal and surface preparation and the amount of time to gain proper strength for the coating material. The fitness function of adaptability is as follows:

$$T = \sum_{i=1}^{18}\sum_{j=1}^{8}\sum_{k=1}^{17}\sum_{l=1}^{4}(T_i^1 a_i \times T_j^2 b_j \times T_k^3 c_k \times T_l^4 d_l)$$

T_i^1 is the normalized time of method i in the first category of solution vectors, T_j^2 is the normalized time of method j in the second category of solution vectors, T_k^3 is the normalized time of method k in the third category of solution vectors and T_l^4 is the normalized time of method l in the fourth category of solution vectors.

Objective values have been calculated for a square foot beam reinforced by 6.7 pounds of steel rebar. Surface preparation methods do not have any values for durability objective, and reinforcing materials have no value for time objective.

Table 3.1 shows the objective values for the first category of solution vectors:

Table 3.1: Objective values for removal methods

Method's name	Price(US$)	Time(minutes)	Durability
Blasting with expansive agents	8.16	10	Very low
Cutting with a high pressure water jet	7.48	10	High
Cutting with a diamond saw	6.25	10	High
Diamond wire cutting	8.31	10	Very high
Mechanical shearing	8.06	10	Moderate
Stitch drilling	8.86	15	High
Thermal cutting	6.86	10	High
Hand-held breakers	5	10	Very low
Boom mounted breakers	6.14	10	Very low
Scabblers	8.71	15	Very high
Scarifier	6.53	10	High
Hydro demolition	6.67	2	Moderate
Hydraulic splitter	12	4	High
Sandblasting	13.12	15	Very high
Shot blasting	16.25	15	Very high
High-pressure water blasting	12.5	5	Moderate

Table 3.2 shows the objective values for the second category of solution vectors:

Table 3.2: Objective values for surface preparation methods

Method’s name	Price(US$)	Time(minutes)
Chemical cleaning	9.28	5
Acid etching	12.5	4
Scabblers	0.67	2
Scarifiers	0.4	1
Grinder	0.48	1.5
Sandblasting	0.87	1
Shotblasting	1.08	1

Table 3.3 shows the objective values for the third category of solution vectors:

Table 3.3: Objective values for coating materials

Material’s name	Price(US$)	Time(days)	Durability
Conventional concrete	7	28	Moderate
conventional mortar	5.5	21	Low
Dry-pack mortar	6.85	5	Moderate
Proprietary repair mortar	8	10	High
Ferrocement	7.26	28	High
Fiber-reinforced concrete	8.43	28	Very high
Magnesium phosphate concrete	7.39	1	Very high
Preplaced-aggregate concrete	8.8	28	High
Rapid-setting cement	8.5	1	Moderate
Shrinkage compensating concrete	8.35	7	High
Silica fume concrete	9.2	5	High
Polymer concrete	8.9	28	High

Table 3.4 shows the objective values for the fourth category of solution vectors:

Table 3.4: Objective values for reinforcement materials

Material's name	Price(US$)	Durability
Galvanized reinforcement	7.5	High
Stainless steel reinforcement	4.29	Moderate
Stainless steel-clad reinforcement	6.7	High
Fiber-reinforced polymer	8	Very high

3.5. Weighted sum method

In this method, each objective is assigned a certain amount of weight regarding its importance in the present project. The value of weights assigned should be between one and zero and the summation of all the weights for all the objectives should be equal to one (Sarker & Liang, 2002).

$$\sum_{i=1}^{m} w_i = w_1 + w_2 + \cdots + w_m = 1$$

$$0 < w_i < 1$$

"m" is the number of objectives in the optimization problem and w_i is the weight assigned to objective i.

By assigning a weight to the objectives the multi-objective optimization problem will be reduced into a single objective problem. In a multi-objective optimization problem there are several fitness functions introducing the problem's objectives. Complicated methods such as genetic algorithm (GA) are required to minimize each function and find the Pareto set. On the other hand in a single-objective optimization problem only one fitness function is dealt with. The formulation is as follows:

$$F = \sum_{i=1}^{m} w_i f_i = w_1 f_1 + w_2 f_2 + \ldots + w_m f_m$$

"m" is the number of objectives in the optimization problem, w_i is the weight assigned to objective i and f_i is the fitness function for objective i.

All the objectives must be either minimized or maximized at the same time. If there exist both objectives to be minimized and maximized, the minimization approach is better to be employed.

In this way, objectives to be maximized should multiply by (-1) so the best value for them would be the smallest.

3.6. Pareto surface

As said before in a multi-objective problem, having a visual tool as a Pareto surface is useful for decision-maker to decide better to be fully aware of sacrifices made and trade-offs (Hajela & lin, 1992). The space that the Pareto surface is drawn in is three dimensional as the number objectives are three. Each objective represents an axis of the Cartesian system, and each point represents the head of a solution vector. The tail of the solution vector is the point (0, 0, 0).

3.7. Employed computational software

The data set used in this research consists of price, durability, dust emission, noise, vibration, wastewater quantity, heat emission, debris size and simplicity for removal methods, price, durability, noise vibration, dust production, wastewater quantity and simplicity for surface preparation methods, price, coefficient of thermal expansion, modulus of elasticity, drying shrinkage and durability for coating materials and price, coefficient of thermal expansion, modulus of elasticity, drying shrinkage and durability for reinforcing materials and Also the acceptable upper and lower bound of noise, vibration, dust emission, heat emission, wastewater quantity, debris size and simplicity and finally coefficient of thermal expansion, drying shrinkage and modulus of elasticity of base material. The mentioned sections should be filled in with proper data, some of which has been discussed in chapters one and two. The data are written in a text file. The employed format is note pad.

The computation software used in this project is MATLAB 2018 R2. Code is written in order to export the expected results and plots mentioned previously based on the discussed data set. MATLAB is a powerful and efficient tool in many engineering areas such as optimization, drawing complicated charts.

3.8. Constraints

Most real-world optimization problems include constraints that must be satisfied. Definition of constraints limits the acceptable solutions and helps us search in a smaller portion of the Pareto front. Figure 3.4 presents a Pareto front in which objective f_1 is constrained to be less than ε_1^c. It is evident that the DM should search for solutions in the left portion of Pareto front (Kalyanmoy). The given figure is a simple example. Constraints put out certain solutions which do not pass them. This process cannot always be shown in a linear presentation as in figure 3.6.

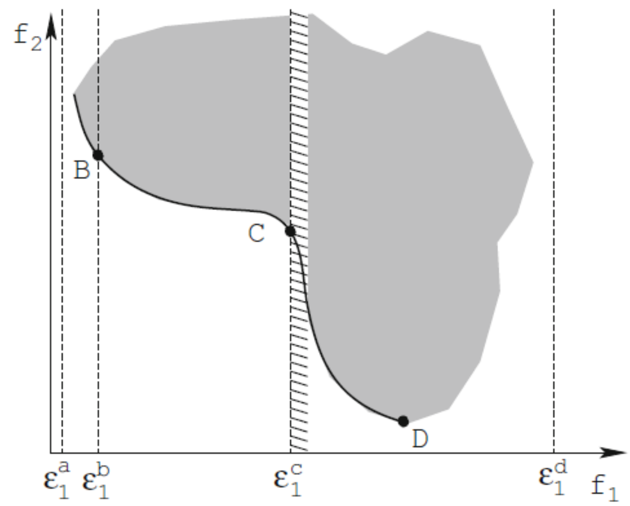


Figure 3.6: Example of constrained Pareto front (Kalyanmoy)

In this research, the considered constraints are noise, vibration, dust emission, heat emission, wastewater quantity, debris size, and simplicity. Those constraints highly depend on the conditions of the project and vary in different conditions. For example in a dense residential area, noise and dust emission will have a high degree of importance and gain closer bounds or heat emission, and vibrations should be much more limited in more damaged and sensitive buildings or debris size and simplicity highly depend on the resources budgets and machinery of the project.

Table 3.5 represents those characteristics of removal methods:

Table 3.5-a: Characteristics of removal methods

Method's name	Noise(dB)	Vibration(Hz)	Dust emission	Heat emission	Wastewater quantity	Debris size	Simplicity
Blasting with expansive agents	100	100	Very low	Very low	None	Large	Simple
Cutting with a high pressure water jet	85	110	None	None	Very high	Very large	Very complex
Cutting with a diamond saw	105	90	High	Moderate	Low	Large	Moderate
Diamond wire cutting	100	95	Moderate	Moderate	Moderate	Large	Very complex

Table 3.5-b: Characteristics of removal methods

Method's name	Noise(dB)	Vibration(Hz)	Dust emission	Heat emission	Wastewater quantity	Debris size	Simplicity
Mechanical shearing	90	102	Moderate	Moderate	Moderate	Very large	Complex
Stitch drilling	87	100	Low	Moderate	Low	Large	Complex
Thermal cutting	60	None	Very low	Very high	Low	Very large	Complex
Hand-held breakers	105	200	High	Very low	None	Large	Very simple
Boom mounted breakers	108	190	High	Very low	Very low	Large	Complex
Scabblers	97	120	High	High	Low	Very small	Complex
Scarifier	100	130	High	High	Low	Very small	Complex
Hydro demolition	88	120	None	None	Very high	Very small	Complex
Hydraulic splitter	85	110	None	None	Very high	Very large	Complex
Sandblasting	110	70	Very high	High	Moderate	Very small	Complex
Shot blasting	115	73	Very high	High	Moderate	Very small	Complex
High-pressure water blasting	90	128	None	None	Very high	Very small	Very complex

Table 3.6 represents those characteristics of surface preparation methods:

Table 3.6-a: Characteristics of surface preparation methods

Method's name	Noise(dB)	Vibration(Hz)	Dust emission	Heat emission	Wastewater quantity	Simplicity
Chemical cleaning	None	None	None	None	Very high	Complex
Acid etching	None	None	None	Low	High	Very complex
Scabblers	97	120	High	High	Low	Complex
Scarifiers	100	130	High	High	Low	Complex

Table 3.6-b: Characteristics of surface preparation methods

Method's name	Noise(dB)	Vibration(Hz)	Dust emission	Heat emission	Wastewater quantity	Simplicity
Grinder	110	100	Moderate	Low	Very low	Moderate
Sandblasting	110	70	Very high	High	Moderate	Complex
Shot blasting	115	73	Very high	High	Moderate	Complex

After applying these constraints, solutions which do not satisfy them should be omitted from the decision making the process.

3.9. Conclusion

In this chapter, solution vectors, objective functions, constraints, and optimization method has been described. Alternative projects can be operated using the same configurations discussed. In the next chapter analysis will be run, and the results and alterations will be discussed.

Chapter 4: Results and discussion

4.1. Introduction

In this chapter, the results of this study will be presented and discussed. The Pareto front for different conditions, including two dimensional coupled objectives and three-dimensional triple objectives, will be drawn. The constraints impact on the study will also be discussed. At the end ten optimum answers will be presented and discussed.

4.2. Coupled objectives Pareto front

operation, the amount of time needed to finish the retrofitting and the durability of the repaired parts after As has been discussed before, this project includes three main objectives: the consuming price for the whole finishing the procedure. A Pareto front is a visual presentation of the objectives concerning each other, so each axis in the n-dimensional (as n is the number of objectives in the problem) space represents an objective. Each point in the space represents a solution vector. Solutions on the Pareto front are the Pareto optimum solutions, and the final answer should be chosen amongst them.

As there are three objectives in this problem, there will be a three-dimensional space to draw the Pareto front. In order to better visualize and understand the relations between the objectives and sacrifices needed to make to turn the situations better for one or two objectives, the Pareto front will first be drawn in a two-dimensional space regarding only two of the objectives. Therefore, there will be three of two dimensional Pareto fonts in this part. Pareto fronts regarding the price coupled with durability, price coupled with execution time and execution time coupled with durability.

4.2.1. Price and durability

One of the most important objectives of any project is the amount of money must be spent on the operations. Durability, on the other hand, is another critical objective which shows its importance through time. Usually, as a method provides higher durability it increases the costs. Although a more durable approach pays off and shows its value in long term. It is the duty of the decision-maker(s) to find a balance between a durable and cheap solution. The purpose of drawing the Pareto front is to help them make such decisions.

Figure. 4.1 shows all the points which have the price objective as they coordinate and durability as the x coordinate without any assigned weights. Assigning weights does not change the overall shape and points on the Pareto surface so there will not be any need to draw the Pareto front regarding the assigned weights.

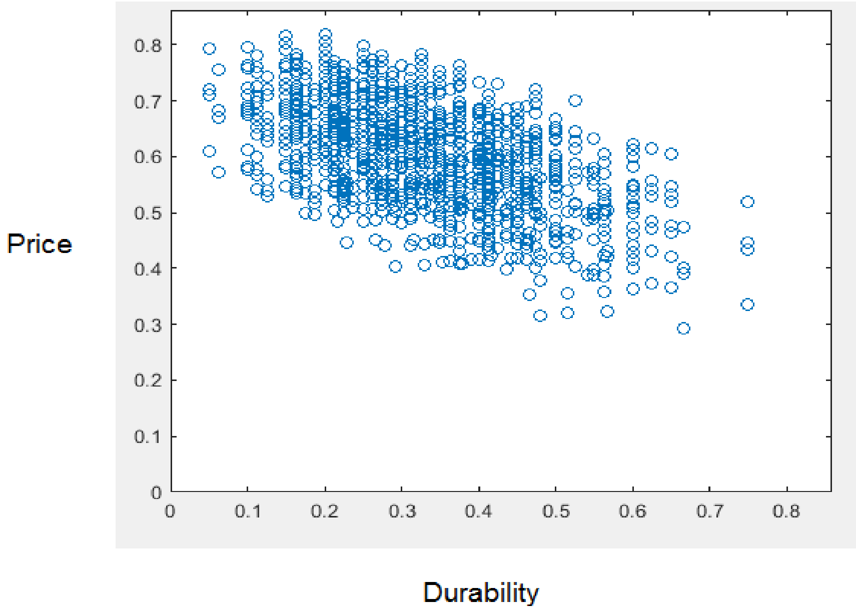


Figure 4.1: Solution vectors in a 2D space with price and durability as y and x-axes

Figure 4.2 shows the Pareto front between price objective and durability objective.

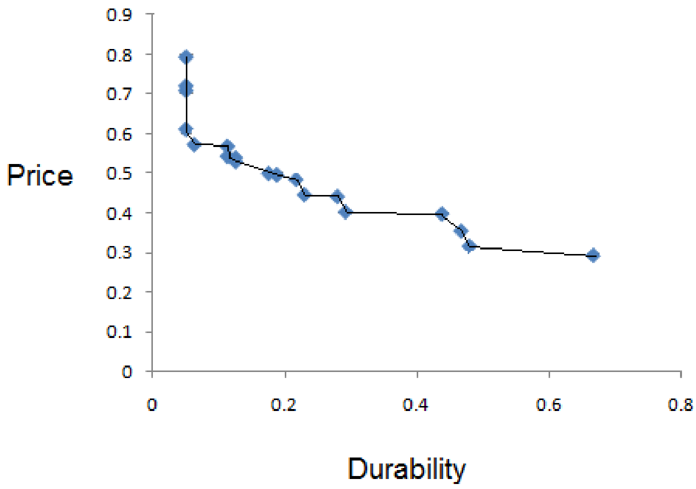


Figure 4.2: The Pareto front between price and durability

The Pareto front is not a continuous surface but a series of discrete points, each of which representing a solution vector. Table 4.1 represents those solutions.

Table 4.1-a: Solution vectors on the price-durability Pareto front

number	Removal method	Surface preparation method	Coating material	Reinforcement material	Normalized durability value	Normalized price value
1	Blasting with a expansive agents	Scarifiers	Conventional concrete	Stainless steel-clad reinforcement	0.6666	0.2926
2	Cutting with a diamond saw	Scarifiers	Conventional concrete	Stainless steel-clad reinforcement	0.4791	0.3158
3	Cutting with a diamond saw	Scarifiers	Conventional concrete	Fiber-reinforced polymer	0.2916	0.4026
4	Cutting with a diamond saw	Scarifiers	Conventional mortar	Galvanized reinforcement	0.2291	0.4458
5	Cutting with a diamond saw	Scarifiers	Dry-pack mortar	Stainless steel-clad reinforcement	0.4375	0.3977
6	Cutting with a diamond saw	Scarifiers	Ferrocement	Fiber-reinforced polymer	0.1875	0.4961
7	Cutting with a diamond saw	Scarifiers	Fiber-reinforced concrete	Galvanized reinforcement	0.1250	0.5393
8	Cutting with a diamond saw	Scarifiers	Fiber-reinforced concrete	Fiber-reinforced polymer	0.1250	0.5294
9	Cutting with a diamond saw	Scarifiers	Magnesium phosphate concrete	Galvanized reinforcement	0.0625	0.5726
10	Cutting with a diamond saw	Scarifiers	Magnesium phosphate concrete	Fiber-reinforced polymer	0.1750	0.4998

Table 4.1-b: Solution vectors on the price-durability Pareto front

11	Cutting with a diamond saw	Scarifiers	Preplaced-aggregate concrete	Galvanized reinforcement	0.1125	0.5430
12	Scabblers	Chemical cleaning	Magnesium phosphate concrete	Galvanized reinforcement	0.0500	0.7935
13	Scabblers	Scabblers	Magnesium phosphate concrete	Galvanized reinforcement	0.0500	0.7093
14	Scabblers	Scarifiers	Conventional concrete	Stainless steel-clad reinforcement	0.4666	0.3543
15	Scabblers	Scarifiers	Conventional concrete	Fiber reinforced polymer	0.2791	0.4411
16	Scabblers	Scarifiers	Conventional mortar	Galvanized reinforcement	0.2166	0.4843
17	Scabblers	Scarifiers	Fiber reinforced concrete	Fiber reinforced polymer	0.1125	0.5679
18	Scabblers	Scarifiers	Magnesium phosphate concrete	Galvanized reinforcement	0.0500	0.6111
19	Scabblers	Scabblers	Magnesium phosphate concrete	Galvanized reinforcement	0.0500	0.7206

4.2.2. Price and execution time

In many cases, it is crucial to finish the operation as soon as possible. However, this is always accompanied by an increase in costs. All the solution vectors in a two-dimensional space with x coordinate of the execution time objective and y coordinate of the price objective are shown in figure 4.3.

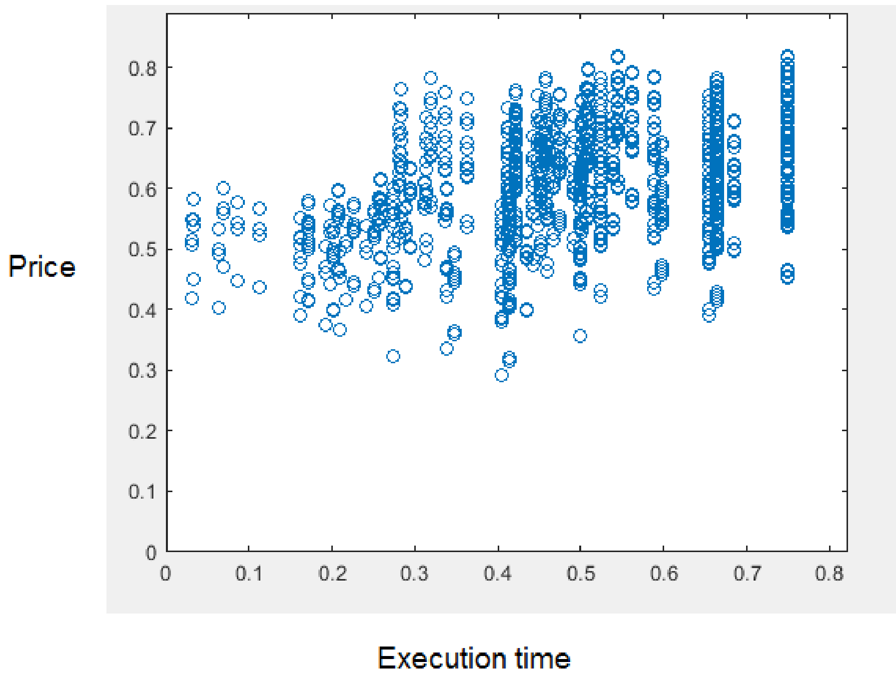


Figure 4.3: Solution vectors in a 2D space with price and execution time as y and x-axes

Figure 4.4 shows the Pareto front between price objective and durability objective.

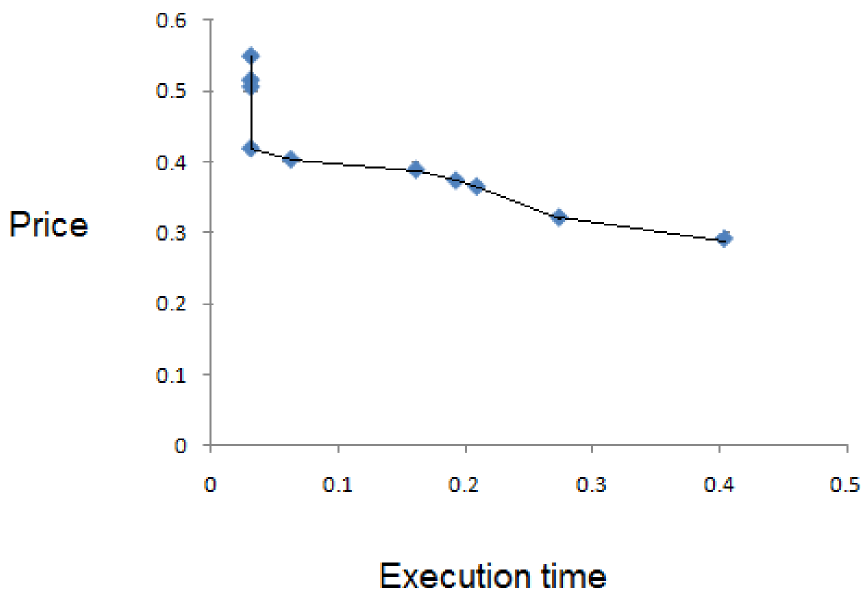


Figure 4.4: The Pareto front between price and execution time

Table 4.2 represents all the solution vectors forming the Pareto front shown in figure 4.4.

Table 4.2: solution vectors on the price-execution time Pareto front

Number	Removal method	Surface preparation method	Coating material	Reinforcement material	Normalized execution time value	Normalized price value
1	Blasting with expansive agents	Scarifiers	Conventional concrete	Stainless steel-clad reinforcement	0.4038	0.2926
2	Blasting with expansive agents	Scarifiers	Dry-pack mortar	Stainless steel-clad reinforcement	0.1929	0.3744
3	Blasting with expansive agents	Scarifiers	Magnesium phosphate concrete	Stainless steel-clad reinforcement	0.1614	0.3898
4	Hydro demolition	Scarifiers	Conventional concrete	Stainless steel-clad reinforcement	0.2740	0.3224
5	Hydro demolition	Scarifiers	Conventional mortar	Stainless steel-clad reinforcement	0.2092	0.3659
6	Hydro demolition	Scarifiers	Dry-pack mortar	Stainless steel-clad reinforcement	0.0631	0.4043
7	Hydro demolition	Scarifiers	Magnesium phosphate concrete	Stainless steel reinforcement	0.0316	0.5159
8	Hydro demolition	Scarifiers	Magnesium phosphate concrete	Stainless steel-clad reinforcement	0.0316	0.4196
9	Hydro demolition	Scarifiers	Magnesium phosphate concrete	Fiber reinforced polymer	0.0316	0.5064
10	Hydro demolition	Scarifiers	Preplaced-aggregate concrete	Galvanized reinforcement	0.0316	0.5496

4.2.3. Execution time and durability

The coupled relation between the execution time and durability is not as strict and straight as of that between price and execution time and between price and durability. However, sometimes decision-makers need to understand the sacrifices on these two objectives if they need to change one of them. All the solution vectors in a two-dimensional space with x coordinate of the execution time objective and y coordinate of the durability objective are shown in figure 4.5.

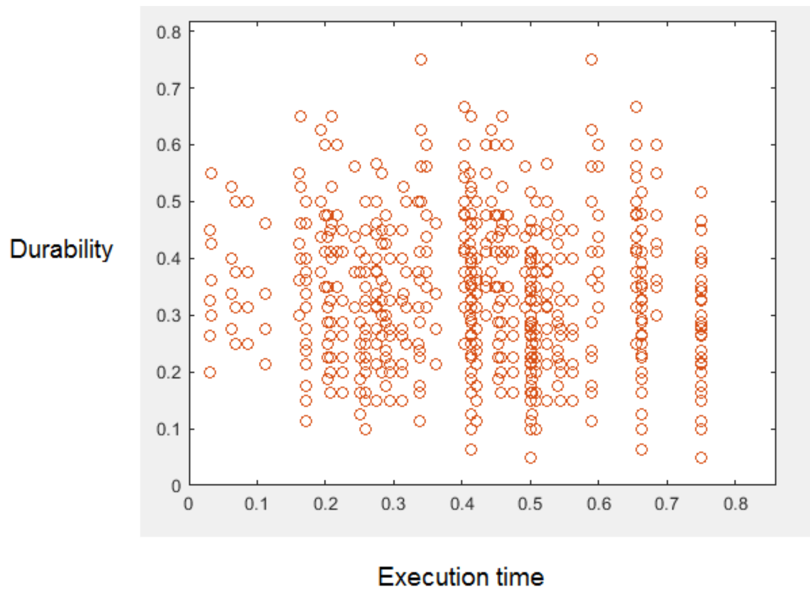


Figure. 4.5 Solution vectors in a 2D space with durability and execution time as y and x-axes

Figure 4.6 shows the Pareto front between price objective and durability objective.

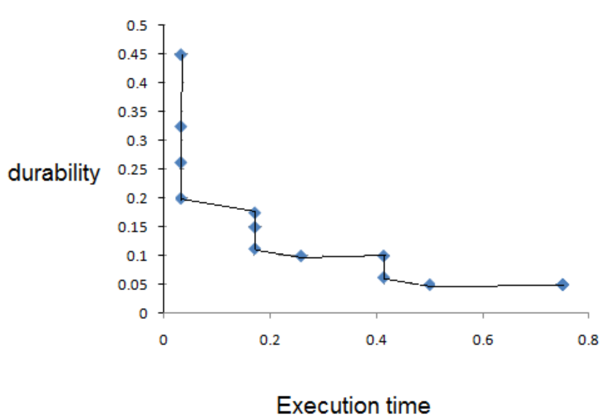


Figure. 4.6 The Pareto front between durability and execution time

Table 4.3 represents all the solution vectors forming the Pareto front shown in figure 4.6.

Table 4.3: solution vectors on the price-execution time Pareto front

Table 4.3-a: Solution vectors on the price-execution time Pareto front

Number	Removal method	Surface preparation method	Coating material	Reinforcement material	Normalized execution time value	Normalized durability value
1	Cutting with a diamond saw	Scarifiers	Magnesium phosphate concrete	Galvanized reinforcement	0.4131	0.0625
2	Cutting with a diamond saw	Scarifiers	Magnesium phosphate concrete	Fiber-reinforced polymer	0.1706	0.1750
3	Cutting with a diamond saw	Scarifiers	Preplaced-aggregate concrete	Galvanized reinforcement	0.1706	0.1125
4	Scabblers	Chemical cleaning	Magnesium phosphate concrete	Galvanized reinforcement	0.7500	0.0500
5	Scabblers	Scabblers	Magnesium phosphate concrete	Galvanized reinforcement	0.7500	0.0500
6	Scabblers	Scarifiers	Magnesium phosphate concrete	Galvanized reinforcement	0.5000	0.0500
7	Scabblers	Scarifiers	Preplaced-aggregate concrete	Galvanized reinforcement	0.2575	0.1
8	Scabblers	Grinder	Magnesium phosphate concrete	Galvanized reinforcement	0.7500	0.0500
9	Scarifiers	Scarifiers	Magnesium phosphate concrete	Galvanized reinforcement	0.4131	0.1000
10	Scarifiers	Scarifiers	Preplaced-aggregate concrete	Galvanized reinforcement	0.1706	0.1500
11	Hydro demolition	Scarifiers	Magnesium phosphate concrete	Stainless steel reinforcement	0.0316	0.3250
12	Hydro demolition	Scarifiers	Magnesium phosphate concrete	Stainless steel-clad reinforcement	0.0316	0.4500

Table 4.3-b: Solution vectors on the price-execution time Pareto front

Number	Removal method	Surface preparation method	Coating material	Reinforcement material	Normalized execution time value	Normalized durability value
13	Hydro demolition	Scarifiers	Magnesium phosphate concrete	Fiber reinforced polymer	0.0316	0.2625
14	Hydro demolition	Scarifiers	Preplaced-aggregate concrete	Galvanized reinforcement	0.0316	0.2000

4.3. Triple objective 3D Pareto front

In this part, the Pareto front regarding both three objectives will be drawn in a three-dimensional space as each axis represents one of the objectives. The two-dimensional space has a better visual preference, but sometimes a decision-maker needs to see and examine the sacrifices of the objectives altogether. However, this is not achievable for more than three objectives. In some analysis with more than three objectives, some of the objectives will be turned into the constraints, so the analysis and the resulting Pareto front could be shown in a three-dimensional space. This is somehow the approach in this study too.

Figure 4.7 shows the solution vectors in a three-dimensional space with the price, durability, and execution time objectives as the three axes.

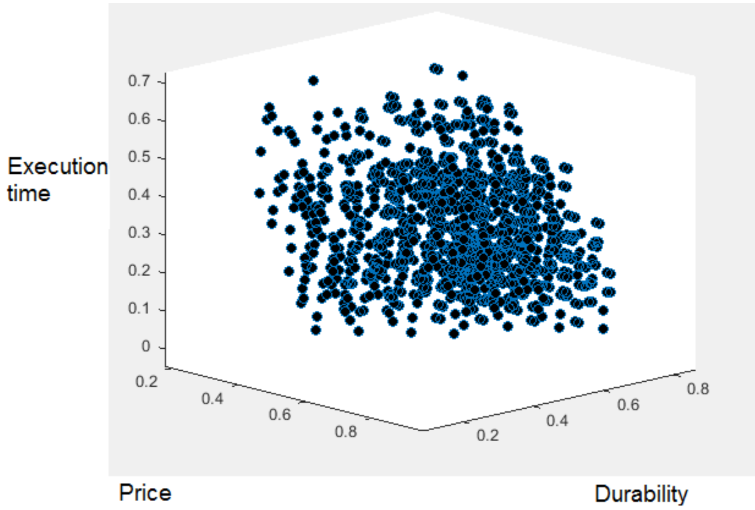


Figure 4.7: Solution vectors with durability, execution time and price as x, y and z axes

The Pareto front is a three-dimensional plate consisting of 59 points. Table A in annex represents those points on the three-dimensional Pareto front. Figure 4.8 represents the points in the three dimentional space consisting the pareto front.

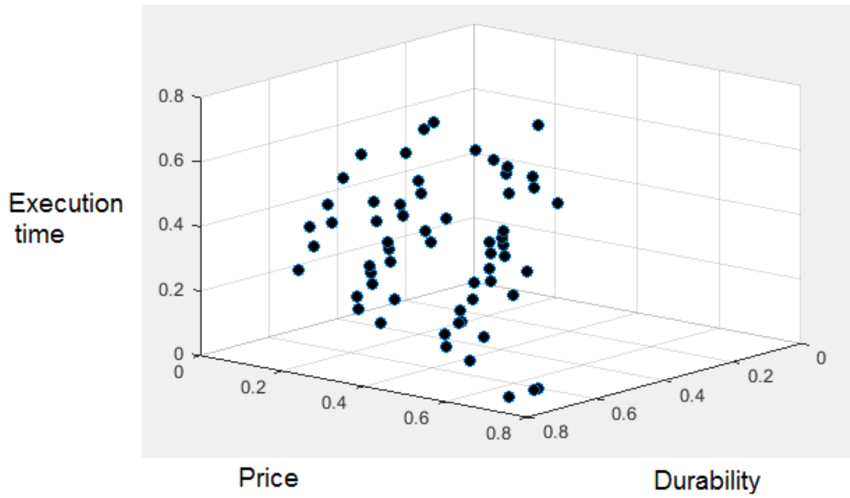


Figure 4.8: The points consisting the 3D pareto front

4.4. Optimum solutions regarding the assigned weights

The final goal of this study is to introduce the optimum solutions. In the present research, the minimization method has been employed, which means the optimum solution has the smallest normalized value. As there are 16 solutions in the first category, 7 solutions in the second category, 12 solutions in the third category and 4 solutions in the fourth category, there will be 5376 solution vectors. The answers will be a chain of four solutions from those four categories. Amongst those 5376 solution vectors, 20 optimum solutions have been chosen to introduce in this part. Table 4.5 represents those 20 sets of optimum solutions with their normalized value.

Table 4.4: 20 optimum solutions of the problem

Table 4.4-a: 20 optimum solutions of the problem

Number	Removal method	Surface preparation method	Coating material	Reinforcement material	Normalized fitness value
1	Hydro demolition	Scarifiers	Magnesium phosphate concrete	Stainless steel-clad reinforcement	0.3481

Table 4.4-b: 20 optimum solutions of the problem

Number	Removal method	Surface preparation method	Coating material	Reinforcement material	Normalized fitness value
2	Cutting with a diamond saw	Scarifiers	Magnesium phosphate concrete	Stainless steel-clad reinforcement	0.3544
3	Hydro demolition	Scarifiers	Dry-pack mortar	Stainless steel reinforcement	0.3602
4	Hydro demolition	Scarifiers	Conventional concrete	Stainless steel reinforcement	0.3616
5	Hydro demolition	Scarifiers	Fiber-reinforced concrete	Fiber-reinforced polymer	0.3626
6	Scarifiers	Scarifiers	Magnesium phosphate concrete	Stainless steel reinforcement	0.3646
7	Cutting with a diamond saw	Scarifiers	Dry-pack mortar	Stainless steel-clad reinforcement	0.3665
8	Cutting with a diamond saw	Scarifiers	Conventional concrete	Stainless steel-clad reinforcement	0.3679
9	Cutting with a diamond saw	Scarifiers	Magnesium phosphate concrete	Galvanized reinforcement	0.3690
10	Hydro demolition	Scarifiers	Conventional mortar	Galvanized reinforcement	0.3747
12	Hydro demolition	Scabblers	Polymer concrete	Stainless steel reinforcement	0.3761
13	Blasting with expansive agents	Scarifiers	Magnesium phosphate concrete	Stainless steel-clad reinforcement	0.3761
14	Scarifiers	Scarifiers	Conventional mortar	Stainless steel reinforcement	0.3766
15	Hydro demolition	Scarifiers	Conventional concrete	Fiber reinforced polymer	0.3771
16	Scarifiers	Scabblers	Polymer concrete	Stainless steel reinforcement	0.3781
17	Scarifiers	Scarifiers	Ferrocement	Fiber-reinforced polymer	0.3791

Table 4.4-c: 20 optimum solutions of the problem

18	Hydro demolition	Scarifiers	Dry-pack mortar	Fiber-reinforced polymer	0.3809
19	Cutting with a diamond saw	Scarifiers	Dry-pack mortar	Galvanized reinforcement	0.3811
20	Cutting with a diamond saw	Scarifiers	Fiber-reinforced concrete	Stainless steel-clad reinforcement	0.382

4.5. Constraint handling

Choosing the limits and constraints of a project is the duty of the decision-maker. Table 4.5 shows the constraints and limits for each characteristic in this project. Those constraints have been chosen regarding the situations governing the conditions of the project. Each solution which could not satisfy those constraints has been omitted from the decision making and optimization process.

Table 4.5: Constraints and limits of the project characteristics

Noise	Vibration	Dust emission	Heat emission	Wastewater quantity	Debris size	simplicity
110	150	High	High	Very high	Large	Complex

4.5.1. Omitted answers regarding the constraints

Any solution which surpasses even one of the limits in table 4.5 has been omitted from the optimization process. Table 4.6 shows the solutions which have been omitted due to their inability to satisfying the constraints.

Table 4.6-a: Omitted answers due to their inability to satisfying the constraints

Number	Name	Solution category	Dissatisfying characteristic
1	Cutting with a high-pressure water jet	Removal methods	Debris size & Simplicity
2	Diamond wire cutting	Removal methods	Simplicity
3	Mechanical shearing	Removal methods	Debris size
4	Thermal cutting	Removal methods	Heat emission & Debris size
5	Hand-held breakers	Removal methods	Vibration

Table 4.6-b: Omitted answers due to their inability to satisfying the constraints

6	Boom mounted breakers	Removal methods	Vibration
7	Sandblasting	Removal methods	Dust emission
8	Shot blasting	Removal methods	Noise & Dust emission
9	High-pressure water blasting	Removal methods	Simplicity
10	Acid etching	Surface preparation methods	Simplicity
11	Sandblasting	Surface preparation methods	Dust emission
12	Shot blasting	Surface preparation methods	Noise & Dust emission

4.5.2. Optimum solutions regardless of constraints

By applying the constraints and limits, many solutions have been omitted from the optimization process. Sometimes it is possible to make an exception to reach to a more economical solution, or some of the concerns could be overcome if needed. A decision-maker should better see the solutions reached without applying any constraints to have a better understanding of such decisions. Table 4.7 represents 20 optimum solutions if the constraints have not been applied.

Table 4.7-a: Optimum solutions without constraints being applied

Number	Removal method	Surface preparation method	Coating material	Reinforcement material	Normalized fitness value
1	Hydro demolition	Scarifiers	Magnesium phosphate concrete	Stainless steel-clad reinforcement	0.3481
2	cutting with a diamond saw	Scarifiers	Magnesium phosphate concrete	Stainless steel-clad reinforcement	0.3544
3	Hydro demolition	Scarifiers	dry-pack mortar	stainless steel reinforcement	0.3602
4	diamond wire cutting	Scarifiers	Magnesium phosphate concrete	stainless steel reinforcement	0.3613
5	Hydro demolition	Scarifiers	Conventional concrete	Galvanized reinforcement	0.3616
6	Hydro demolition	Scarifiers	Fiber-reinforced concrete	Stainless steel-clad reinforcement	0.3626

Table 4.7-b: Optimum solutions without constraints being applied

Number	Removal method	Surface preparation method	Coating material	Reinforcement material	Normalized fitness value
7-	Scarifiers	Scarifiers	Magnesium phosphate concrete	Galvanized reinforcement	0.3646
8	Cutting with a high-pressure water jet	Scarifiers	Magnesium phosphate concrete	Stainless steel-clad reinforcement	0.3660
9	Cutting with a diamond saw	Scarifiers	dry-pack mortar	stainless steel reinforcement	0.3665
10	Thermal cutting	Scarifiers	Fiber-reinforced concrete	Stainless steel-clad reinforcement	0.3677
11	Cutting with a diamond saw	Scarifiers	Conventional concrete	stainless steel reinforcement	0.3679
12	Cutting with a diamond saw	Scarifiers	Fiber-reinforced concrete	Fiber-reinforced polymer	0.3690
13	Diamond wire cutting	Scarifiers	Conventional mortar	stainless steel reinforcement	0.3734
14	Hydro demolition	Scarifiers	Conventional concrete	Galvanized reinforcement	0.3747
15	Diamond wire cutting	Scabblers	Polymer concrete	stainless steel reinforcement	0.3748
16	Diamond wire cutting	Scarifiers	Ferrocement	Fiber-reinforced polymer	0.3758
17	Hydro demolition	Scarifiers	Proprietary repair mortar	Galvanized reinforcement	0.3761
18	Hydro demolition	Scabblers	Shrinkage compensating concrete	Fiber-reinforced polymer	0.3761
19	Blasting with expansive agents	Scarifiers	Magnesium phosphate concrete	Stainless steel-clad reinforcement	0.3761
20	Scarifiers	Scabblers	Polymer concrete	Fiber-reinforced polymer	0.3766

4.6. Real model

In the present research all the configurations on constraints, weights and characteristics assigned to the retrofitting methods are decided in respect to a concrete stuctured seven floor residential building in Shahid Vahedi street, Kermanshah, Iran. Figure 4.9 shows the plan for the first floor. The rest of the floors have the same plan.

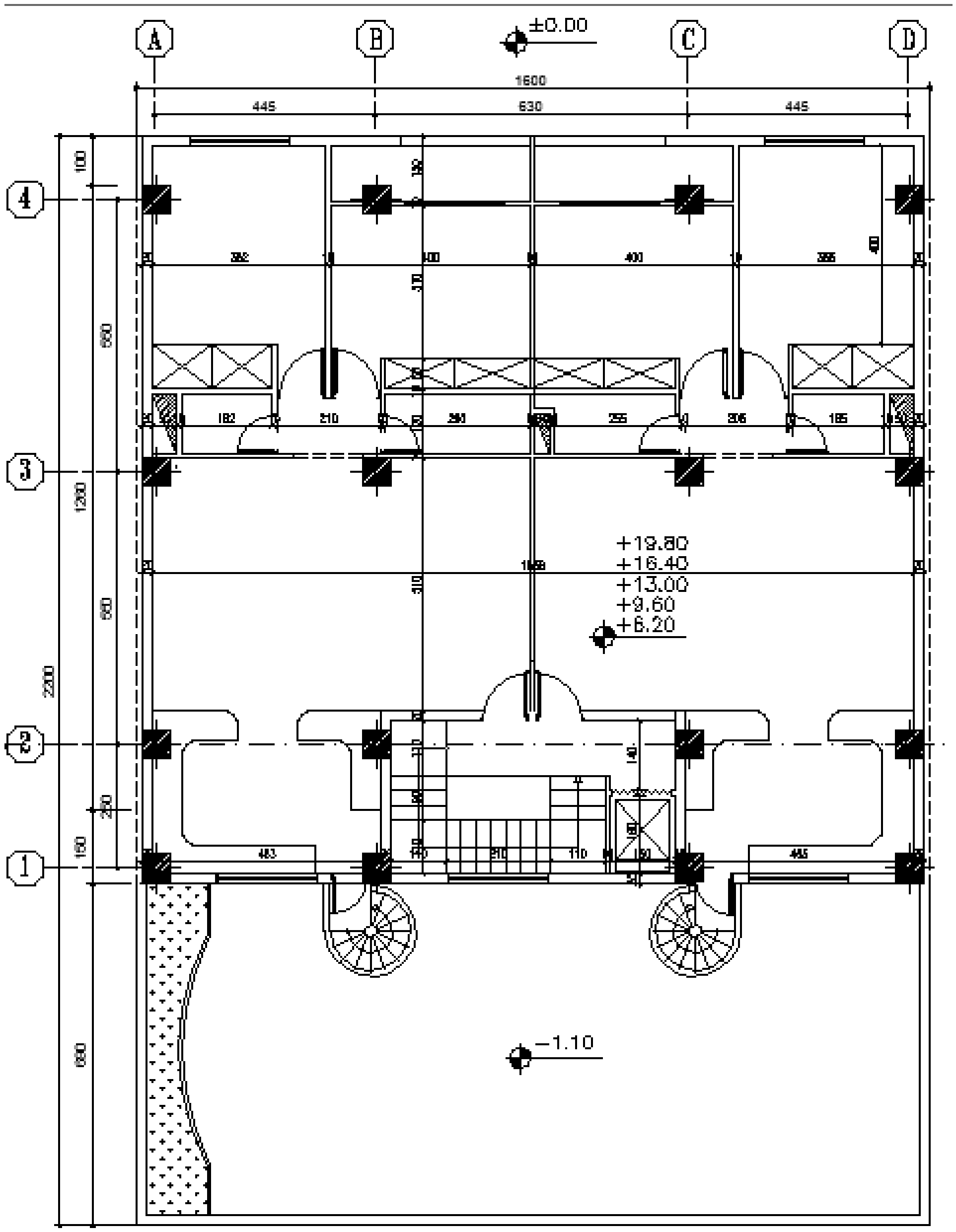


Figure 4.9: Residential floors plan

Note that the unit for spacings is centimeter and the unit for elevations is meter.

The building is damaged under the earthquake load took place in 12 november 2017. The moment magnitude of the earthquake was reported 7.3 with the intensity of “severe” (https://www.usgs.gov 2019). The building was damaged in several parts including cracking in beams and beams. The study is aimed to find optimum solutions to retrofit damaged beams. Figure 4.10-12 shows the three different sets of plans that specifies the type of beams for each part of the building.

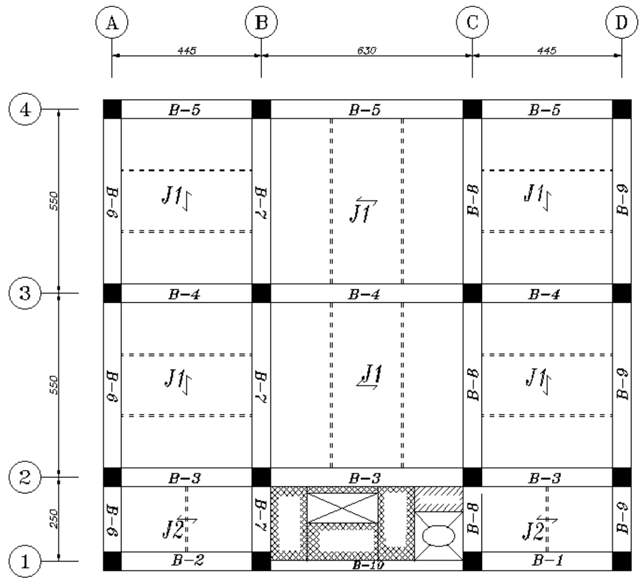


Figure 4.10: The plan to specify beam and floor types for elevation 0.00

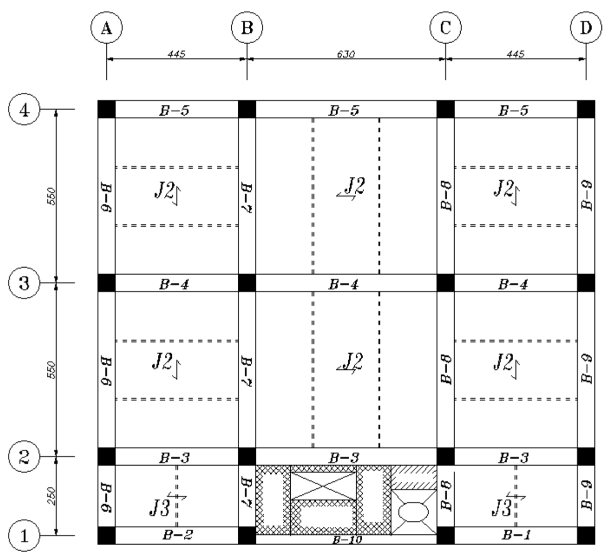


Figure 4.11: The plan to specify beam and floor type for elevation 2.80

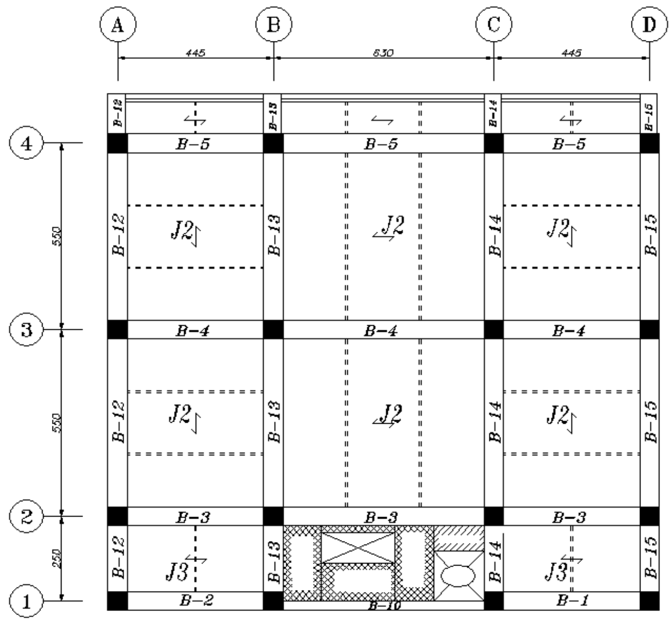


Figure 4.12: The plan to specify beam and floor type for elevations 6.20, 9.60, 13.00, 16.40, 19.60 and 23.20

Note that the unit for spacings is centimeter and the unit for elevations is meter.

The configurations on the rebar length, volume of required coating materials and the surface area to do the removal and prepatation have been made due to the beam type B-1. The results are indeed able to generalize to the whole building beam sections.

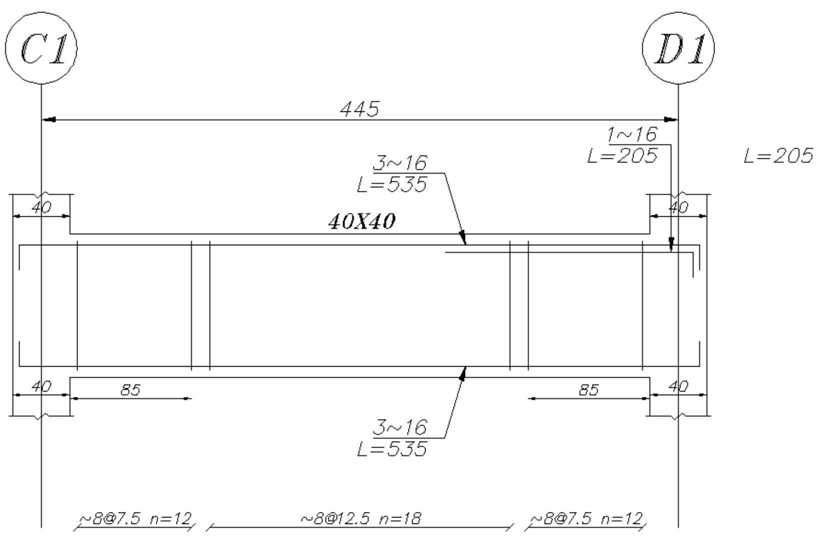


Figure 4.13: Details of beam type B-1

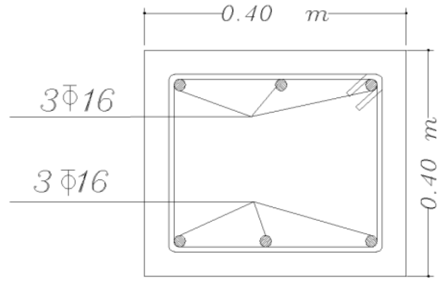


Figure 4.14: Section of beam type B-1

4.7. Conclusions

In this chapter, the analysis results have been presented and discussed. All the numbers, including weights, constraints, and coefficients could be changed if needed. The purpose of this study is not to offer a series of solutions for a specific building but to propose an optimization approach to reach the best solutions possible in a certain situation.

Chapter 5: Conclusions

5.1. Introduction

The present study proposes and tests a method of multi-objective optimization to find a group of proper solutions in repairing damaged concrete sections. As described in chapters three, this research is based on a weighted sum method with assigning certain weights to each objective of the problem. Each of the solution vectors has a series of certain characteristics that affect the decision-making process. Chapter three introduces the method and application of the optimization method along with the way these characteristics are being used to propose optimal and proper solutions.

In chapter four, the results have been presented via diagrams and tables. The reader can go through and find different optimal solutions, each of which satisfying objectives to a certain level.

All the coefficients can be changed if necessary to make alternative configurations if needed as the present study is not about reaching specific solutions for a single building but to propose and test a method to help the decision-maker find proper answers to repair a damaged building.

5.2. Results of the research

In this section, the results of the research answering the fundamental questions in chapter one will be presented. The fundamental questions in this study are as follows:

1. Is multi-objective optimization a legitimate method to find solution methods in concrete retrofitting?

2. Could it help the decision-making process to optimize the problem with a more significant number of objectives?

3. How the constraints affect the results of optimization and what difference would it make if those constraints are not applied?

5.2.1. Applicability of multi-objective optimization

As has been said in chapters one and three, for almost every engineering problems, there exist multiple solutions, each of which satisfies the objectives into a certain degree. An excellent approach to solve such problems and find proper solutions is multi-objective optimization. As the results in chapter four have shown, there will be a set of Pareto optimal answers satisfying the objectives of the problem.

With a weighted sum method, the problem has been reduced mathematically into a single-objective optimization problem so a series of optimal answers sorted by their weighted normalized values could be proposed. As the answers seem applicable in the given situation, and objectives are satisfied into the desired degree, the weighted sum multi-objective optimization method seems to have been working in this case. The decision-maker can, of course, make additional or alternative configuration in the process. For example, if a certain method is not available in the given situation or some constraints can be neglected, the decision-maker can make the related change in the process.

5.2.2. Variation of objectives

In the present study, three objectives, including price, execution time, and durability have been considered. Two types of Pareto fronts have been drawn. In section 4.2 of chapter four the two-dimensional Pareto fronts are shown proposing the relation between three couples of objectives. The solution vectors on those fronts are brought in separate tables. Section 4.3 of chapter four discusses the three-dimensional Pareto front considering all three objectives of the problem. The Pareto optimal solutions in the three-objective condition are also shown in table 4.4. There can be seen a slight difference in optimal solutions.

This gives a good understanding of objective handling and the amount of difference made if an objective being neglected. Another approach in the weighted sum method is to change the assigning weights in the optimization process. If the decision-maker decides an objective to be less affecting in the optimization, they can reduce the assigning weight for that objective.

5.2.3. The impact of constraints

The results in section 4.5 of chapter four show the degree that the constraints change the optimal answers to the problem. Sometimes a specific constraint can be neglected in a certain situation, or some operations can be carried out to make the solution satisfy a constraint. For example, with spending slightly more time and money, it is possible to get the debris size smaller to pass that constraint.

In section 4.5.2, the optimal solutions, regardless of constraints have been presented. The decision-maker should see what amount of difference it makes to neglect a certain constraint to make such decisions. Table 4.8 is an example of such data the decision-maker needs to study.

5.3. Suggestions for further researches

Even though in this research, a modern approach has been employed, there are still several limitations in the study. Some of those limitations are as follows:

- As the visual presentation of the Pareto front does not allow drawing in a more than three-dimensional space, only three objectives have been considered in the optimization problem.

- The employed optimization method, which is the weighted sum method is a simple approach avoiding any complexity.

- The solution vectors have only been chosen from the concrete removal methods, surface preparation methods, coating material and reinforcement materials brought in the concrete repair guide "ACI 546R-04".

- The study is limited to the concrete structure buildings.

Considering the above limitations, there follow the suggestions for further studies and researches:

- Considering a different number of objectives

- Employing a non-linear fitness function for the objectives

- Optimize solutions for repairing a steel structure building

- Employing other optimization methods

- Choosing an alternate solution vectors set.

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Annexes

Table A.1: solution vectors on the three dimensional Pareto front

Number	Removal method	Surface preparation method	Coating material	Reinforcement material	Normalized price value	Normalized execution time value	Normalized durability value
1	Blasting with expansive agents	Scarifiers	Conventional concrete	Stainless steel reinforcement	0.3889	0.4038	0.5416
2	Blasting with expansive agents	Scarifiers	Conventional concrete	Stainless steel-clad reinforcement	0.2926	0.4038	0.6666
3	Blasting with expansive agents	Scarifiers	Conventional concrete	Fiber reinforced polymer	0.3794	0.4038	0.4791
4	Blasting with expansive agents	Scarifiers	Dry-pack mortar	Stainless steel-clad reinforcement	0.3744	0.4038	0.6250
5	Blasting with expansive agents	Scarifiers	Ferrocement	Stainless steel-clad reinforcement	0.3861	0.4038	0.5625
6	Blasting with expansive agents	Scarifiers	Magnesium phosphate concrete	Stainless steel reinforcement	0.4861	0.1614	0.4250
7	Blasting with expansive agents	Scarifiers	Magnesium phosphate concrete	Stainless steel-clad reinforcement	0.3898	0.1614	0.5500
8	Blasting with expansive agents	Scarifiers	Magnesium phosphate concrete	Fiber reinforced polymer	0.4766	0.1614	0.3625
9	Cutting with diamond saw	Scarifiers	Conventional concrete	Stainless steel reinforcement	0.4121	0.4131	0.3541
10	Cutting with diamond saw	Scarifiers	Conventional concrete	Stainless steel-clad reinforcement	0.3158	0.4131	0.4791

Table A.2: solution vectors on the three dimensional Pareto front

Number	Removal method	Surface preparation method	Coating material	Reinforcement material	Normalized price value	Normalized execution time value	Normalized durability value
11	Cutting with diamond saw	Scarifiers	Conventional concrete	Fiber reinforced polymer	0.4026	0.4131	0.2916
12	Cutting with diamond saw	Scarifiers	Conventional mortar	Galvanized reinforcement	0.4458	0.4131	0.2291
13	Cutting with diamond saw	Scarifiers	Conventional mortar	Stainless steel-clad reinforcement	0.3593	0.3482	0.5625
14	Cutting with diamond saw	Scarifiers	Dry-pack mortar	Stainless steel reinforcement	0.4940	0.2021	0.3125
15	Cutting with diamond saw	Scarifiers	Dry-pack mortar	Stainless steel-clad reinforcement	0.3977	0.2021	0.4375
16	Cutting with a diamond saw	Scarifiers	Dry-pack mortar	Fiber-reinforced polymer	0.4845	0.2021	0.2500
17	Cutting with diamond saw	Scarifiers	Ferrocement	Stainless steel-clad reinforcement	0.4093	0.4131	0.3750
18	Cutting with diamond saw	Scarifiers	Ferrocement	Fiber reinforced polymer	0.4961	0.4131	0.1875
19	Cutting with diamond saw	Scarifiers	Fiber reinforced concrete	Galvanized reinforcement	0.5393	0.4131	0.1250
20	Cutting with diamond saw	Scarifiers	Fiber reinforced concrete	Stainless steel-clad reinforcement	0.4426	0.4131	0.3125
21	Cutting with a diamond saw	Scarifiers	Fiber-reinforced concrete	Fiber-reinforced polymer	0.5294	0.4131	0.1250

Table A.3: solution vectors on the three dimensional Pareto front

Number	Removal method	Surface preparation method	Coating material	Reinforcement material	Normalized price value	Normalized execution time value	Normalized durability value
22	Cutting with diamond saw	Scarifiers	Magnesium phosphate concrete	Galvanized reinforcement	0.5726	0.4131	0.0625
23	Cutting with diamond saw	Scarifiers	Magnesium phosphate concrete	Stainless steel reinforcement	0.5093	0.1706	0.2375
24	Cutting with diamond saw	Scarifiers	Magnesium phosphate concrete	Stainless steel-clad reinforcement	0.4130	0.1706	0.3625
25	Cutting with diamond saw	Scarifiers	Magnesium phosphate concrete	Fiber reinforced polymer	0.4998	0.1706	0.1750
26	Cutting with diamond saw	Scarifiers	Preplaced-aggregate concrete	Galvanized reinforcement	0.5430	0.1706	0.1125
27	Scabblers	Chemical cleaning	Magnesium phosphate concrete	Galvanized reinforcement	0.7935	0.7500	0.0500
28	Scabblers	Scabblers	Preplaced-aggregate concrete	Galvanized reinforcement	0.7093	0.7500	0.0500
29	Scabblers	Scarifiers	Conventional concrete	Stainless steel-clad reinforcement	0.3543	0.5000	0.4666
30	Scabblers	Scarifiers	Conventional concrete	Fiber reinforced polymer	0.4411	0.5000	0.2791
31	Scabblers	Scarifiers	Conventional mortar	Galvanized reinforcement	0.4843	0.5000	0.2166
32	Scabblers	Scarifiers	Fiber reinforced concrete	Fiber reinforced polymer	0.5679	0.5000	0.1125
33	Scabblers	Scarifiers	Magnesium phosphate concrete	Galvanized reinforcement	0.6111	0.5000	0.0500
34	Scabblers	Scarifiers	Magnesium phosphate concrete	Stainless steel-clad reinforcement	0.4515	0.2575	0.3500
35	Scabblers	Scarifiers	Magnesium phosphate concrete	Fiber reinforced polymer	0.5383	0.2575	0.1625

Table A.4: solution vectors on the three dimensional Pareto front

Number	Removal method	Surface preparation method	Coating material	Reinforcement material	Normalized price value	Normalized execution time value	Normalized durability value
36	Scabblers	Scarifiers	Preplaced-aggregate concrete	Galvanized reinforcement	0.5815	0.2575	0.1000
37	Scabblers	Grinder	Magnesium phosphate concrete	Galvanized reinforcement	0.7206	0.7500	0.0500
38	Scarifiers	Scarifiers	Conventional concrete	Stainless steel-clad reinforcement	0.3202	0.4131	0.5166
39	Scarifiers	Scarifiers	Conventional concrete	Fiber reinforced polymer	0.4070	0.413	0.3291
40	Scarifiers	Scarifiers	Conventional mortar	Galvanized reinforcement	0.4502	0.413	0.2666
41	Scarifiers	Scarifiers	Dry-pack mortar	Stainless steel-clad reinforcement	0.4021	0.2021	0.4750
42	Scarifiers	Scarifiers	Dry-pack mortar	Fiber reinforced polymer	0.4888	0.2021	0.2875
43	Scarifiers	Scarifiers	Fiber reinforced concrete	Stainless steel-clad reinforcement	0.4470	0.41310	0.3500
44	Scarifiers	Scarifiers	Fiber reinforced concrete	Fiber reinforced polymer	0.5338	0.4131	0.1625
45	Scarifiers	Scarifiers	Magnesium phosphate concrete	Galvanized reinforcement	0.5770	0.4131	0.1000
46	Scarifiers	Scarifiers	Magnesium phosphate concrete	Stainless steel-clad reinforcement	0.4174	0.1706	0.4000
47	Scarifiers	Scarifiers	Magnesium phosphate concrete	Fiber reinforced polymer	0.5042	0.1706	0.2125
48	Scarifiers	Scarifiers	Preplaced-aggregate concrete	Galvanized reinforcement	0.5474	0.1706	0.1500
49	Hydro demolition	Scarifiers	Conventional concrete	Stainless steel-clad reinforcement	0.3224	0.2740	0.5666
50	Hydro demolition	Scarifiers	Conventional concrete	Fiber reinforced polymer	0.4092	0.2740	0.3791

Table A.5: solution vectors on the three dimensional Pareto front

Number	Removal method	Surface preparation method	Coating material	Reinforcement material	Normalized price value	Normalized execution time value	Normalized durability value
51	Hydro demolition	Scarifiers	Conventional mortar	Galvanized reinforcement	0.4524	0.2740	0.3166
52	Hydro demolition	Scarifiers	Conventional mortar	Stainless steel-clad reinforcement	0.3659	0.2092	0.6500
53	Hydro demolition	Scarifiers	Dry-pack mortar	Stainless steel reinforcement	0.5006	0.0631	0.4000
54	Hydro demolition	Scarifiers	Dry-pack mortar	Stainless steel-clad reinforcement	0.4043	0.0631	0.5250
55	Hydro demolition	Scarifiers	Dry-pack mortar	Fiber reinforced polymer	0.4910	0.0631	0.3375
56	Hydro demolition	Scarifiers	Magnesium phosphate concrete	Stainless steel reinforcement	0.5159	0.0316	0.3250
57	Hydro demolition	Scarifiers	Magnesium phosphate concrete	Stainless steel-clad reinforcement	0.4196	0.0316	0.4500
58	Hydro demolition	Scarifiers	Magnesium phosphate concrete	Fiber reinforced polymer	0.5064	0.0316	0.2625
59	Hydro demolition	Scarifiers	Preplaced-aggregate concrete	Galvanized reinforcement	0.5496	0.0316	0.2000