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Original Article

Guidelines for structural optimization and sustainable retrofitting of re-purposed buildings using BIM

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Abstract

Nowadays energy problems resulting from the building industry become very polluting along with the high expenses of the building operation. Designers tend to propose another solution which is the refurbishment of old buildings to be energy-optimized and more efficient. As a result, some solutions are addressed to prioritize keeping the architectural theme of the city as well as reducing land use. An extensive investigation is conducted to review past research approaches regarding energy optimization requirements as well as scoping on structural optimization through building refurbishment. Structural optimization resulting from structural repurposing is not studied in depth recently, as a result, suggested guidelines combining energy and structural optimization are developed to recheck the stability of structural elements and use updated energy techniques with environmentally friendly merits. Building Information Modelling (BIM) adopted, is a modelling concept where the information contributed by multi- disciplinary engineering branches is interpreted in a model to be visualized for all. Thus, BIM allows fast assessment of such process from a cost and materials perspective point of view. These guidelines will be validated to facilitate the process of structural assessment in Egypt and can be used as a milestone in combining structure and Energy optimization.

1. INTRODUCTION

Energy problems were first flagged on the horizon after the six-day war between Egypt and Israel (1973), and the ban of oil on western countries had its impact on them thus the western community started to realize the problem. They worked on their thermal comfort inside buildings to be running without fossil fuel as much as possible, however not only the strategic dependence on fossil fuel that makes the western world move but also the environmental problem rose as well. During the 90s of the past centuries, the world started to notice the environmental effect of the mass production industry globally and quickly understood that the pattern is going to be very drastic if no action is to be taken. Energy consumption of the buildings is categorized to six phases during its life cycle as follows; Extraction of materials, manufacturing, construction, operation and maintenance, demolition, or recycling. Materials extraction and operational phases have the highest impact on environment from energy consumption point of view that is used over the building service life[1]. As a result, 36% of global energy consumption is caused by the building sector and 40% of greenhouse gas (GHG) emissions[2], and it is increasing annually by 1% due to the building operation phase. Thus, researchers are now targeting a new approach to reduce energy consumption either from the construction or operational phase. As a part of reducing energy during the material acquiring phase and operational phase is to rehabilitate old buildings to be structurally sustainable and energy-efficient which will add to the building value and preserve the architectural theme of the location and save time compared to building new construction. In this paper, we will suggest guidelines to help different parties involved in projects related to building optimization concerning energy or structural use, either repurposing or renovation as is. Many examples implemented this approach, as shown in Figure 1 and Figure 2, such as Tate Museum as shown in and St. John Library (Winnipeg, Canada) Tate Museum is repurposed from electric power station to Museum and a gallery, while St. John Library is extended with a glass façade. The research aim is to derive guidelines for multi-disciplinary rehabilitation projects. The main disciplines assumed in this study are energy and structural optimization.

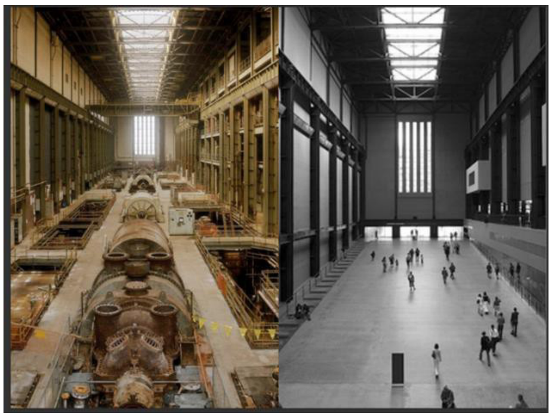

Fig. 1: Tate Modern Museum before and after renovation from outside[1].

Fig. 2: St. John Library, Canada [2].

2. LITERATURE

Many researchers tried to work on building sustainability in the retrofitting process due to the global orientation towards energy preservation. Consequently, it will reduce the running cost of the building. A lot of techniques are adopted from active and passive techniques and introduced on a new building or existing one as stated by Oddyssee Mure[3], who stated that existing or retrofitted buildings consume more than 40% of total global energy. However, the global thermal regulation states that if a building is constructed after 1948 and of a surface more than 1000m2 and renovation cost is more than 25% of the building value; the overall energy consumption must be reduced by 30%[4].

Galvin[5] emphasized that thermally comfortable houses consumed about 70% fossil fuel based in the EU which affect the EU's GHG by 25%. It is concluded that cube and small-shaped buildings are much conservative than irregular large ones in thermal retention. Even if a new building uses hardly any energy over its lifetime, it still takes 25–50 years before it starts to pay its way in comparison to an old building modestly renovated to reduce its emissions by 1 to 2 tons of CO^2 per year. He also proposed that household retrofitting for heating or cooling on an existing building could save more than the renewable energy if used. He also conducted a study bet ween high standard and normal thermal renovation and found that the standard renovation is more than the other.

International Energy Agency[6] reported that light approximately consumes 19% of the global electric energy consumption nearly one-fifth of the global consumption, also responsible for (40-50%) of global greenhouse gas effect, and it is expected to be increased by 50% of its current value by 2030. The saving potential is proposed in their report with different techniques and strategies that could reach (20-93%).

Many countries, tried to formulate rating systems such as LEED and BREEM, to set the limits to be used for engineers in the energy retrofitting process to meet a certain level of energy sustainability and define the required output for reaching Sustainability Development Goals (SDGs). However, none of these programs proposed a guidelines or steps on how to adaptively reuse a building from structural retrofitting point of view.

Recently, for facilitating the engineer job in combining different perspectives in structure's optimization, many research is done using the BIM tool. Eleftheriadis[7] studied the optimization of structure regarding cost and CO^2 together to show that the BIM-based approach could combine two approaches, his paper targeted the slab, column size, and column reinforcement and found out that the main contributors to structure optimization are slab thickness and structure layout and that the building layout and form is a major parameter in cost and carbon print reducers. According to L.Mei and Q.Wang[8] structure optimization is divided into four main categories: size optimization (related to the cross-section area of the building and the structural members are the variables), shape optimization (related to building configuration where its coordinates are the variables), topology optimization (related to how building joints are supported to delete unnecessary structure members), Multi-objective optimization (which consider two or more optimization principles). Generally, four techniques must be done for any type of optimization which is: Modelling technique, Formulation of optimization (problem and variable definition), optimization method (type of method used to reach this optimization), Computational tool (referring to the software used to perform our design which is commonly used SAP2000, ETABS and REVIT). Therefore, multi - optimization is still in need of more research. However, none of these attempts was organized or had a defined sequence.

Ciotta, *et al.*[9], concluded that the link between structural optimization and BIM and structural misses a real state-of-the-art. It is concluded that BIM outcomes are many such as structural modelling, exporting to different analysis programs, producing shop drawings, early detection of errors or structure obstructions, comparing different solutions, seismic assessment on the building, structure modelling retrofitting modelling and assessment and finally building health monitoring. They also stated that structure optimization using BIM has a gap in this link, as the building will be well monitored in its performance (e.g., temperature, light, etc.). And because BIM- based program (REVIT) has the property of multidisciplinary contribution thus new structures will be well monitored such as bridges and their maintenance on the contrary of before. In this regard, a serio us attempt was conducted on a prototype case study by Hairudin, *et. al.*[10] whereby optimizing the envelope of the existing building and a result of 44.78% reduction of overall thermal transfer value is achieved. Thus, indicated that integrating BIM with different programs (structure optimization program and energy performance optimization program) could speed up the optimization process.

U.Vitiello *et al.*[9], conducted a case study by applying different retrofitting techniques. It aims to identify the optimal safety level concerning its strengthening interventions and economic losses associated. A large amount of data concerning multidisciplinary optimization, such as damage and cost analysis of the structural elements, are processed using the BIM tool. A wider methodology is used for optimizing seismic retrofit strategy, considering both safety and economic features. S.Cruza *et al.*[11], reviewed current practices and regulations and proposed criteria to link decision-making in seismic rehabilitation of structures. Many methodologies including BIM are adopted to involve all participating stakeholders. The suggested criteria are applied and tested on a real decision-making case process to increase transparency, especially with environmentally oriented stakeholders.

Another framework for the optimization of steel jacketing retrofitting interventions on RC columns is presented by F.Di *et al.*[12]. The study aimed to provide the amount of steel jacketing reinforcement as well as topological optimization. An iterative solution is conducted to reach the most optimum jacketing solution to reach a specific safety level with effective and sustainable reduced retrofitting cost. A.Okakpu *et al.*[13] identified four distinct components comprising refurbishment attributes, environmental influence factors, stakeholders' interaction, and structure optimization to realize BIM on refurbishment projects. The framework is proposed using barriers and research direction to facilitate the identification of the four dimensions that encompass the main factors that impact BIM adoption specific to refurbishment projects and at the same time guide BIM research for future refurbishment studies. However, a detailed investigation needs to be done on the environmental factors and the refurbishment attributes to clarify and implement them on multi-discipline optimization projects.

From the previous literature, it is clear that no combination between structural and environmental optimization is considered before for rehabilitating an old building.

2.1. Energy Optimization Technical Review

Design guidelines for sustainable and solar-optimized building Design (Integrated Design Process) or (IDP) are proposed by of 25 scientists, the guidelines explain why IDP is important, and it has impact on different dimensions and design consideration, which defines the difference between the traditional approach and the integrated one.

The traditional design is implemented without any consideration of the thermal comfort or the running cost on the client after its completion; the integrated design is involved from the first stages using an integrated team composed of the architect, structural, mechanical, electrical engineers along with design facilitator, who is aware of energy engineering and management engineering. The design process development model defines the general sche me on how to monitor complex design issues by addressing only the relevant parties on the problem.

The loop begins with context analysis where the conflict is segregated from the context to the generic process stage. An entire workflow is tabulated to be easily monitored and modified along with the structure stage. Each design is identified with certain factors (Actors, Goals, and Activities) in which both phases are integrated to be changed from linear to iterative and finally reach the end of the loop, where the Key issues and Recommendations are sorted out and fixed before entering the next phase (Design process Recommendations). Then, developing the requirements for the Design process recommendation, and finally implementing the integrated design process phase providing key performance indicators on how the facility works and its energy audit.

Clément[14] adopted an office building because it consumes more energy due to differences in activities, (about 58% more), according to (World Business Consulting Sustainable Developments). Passive sustainability.

(Rehabilitation of existing buildings) is studied and scoped in this research. It is concluded that Reinforcing building envelope and lighting efficiency is more saving compared to improving the following systems; heating system, cooling system, ventilation, HVAC. It is concluded that, energy could be saved by 10% of the energy used only by light work. From the case study, it is found that heavy renovation is the most expensive and the most efficient at the same time. Trying to reach green certification to add the value of the building in these two cases is a high investment compared to direct energy saving cost. However, energy-saving will be reached by either one of those strategies. As a result, to acquire a certification, for multi-purpose retrofitting strategies, we need to address the direct reduction approach.

2.2. Structural Optimization Technical Review

Few types of research scoped on structure rehabilitation. An extensive investigation on the techniques and modes of failure of 12 case studies is presented by Aguilar[15]. These buildings were damaged by an extensive earthquake that occurred in Mexico City in September 1995. However, many of the affected buildings were already retrofitted from 1985 when another earthquake hit the same city earlier. Due to the documentation of the

rehabilitated buildings and sharing knowledge. He was able to analyse these case studies and concluded that:

• Considering damage study of buildings is very important to the rehabilitation design scheme,

• Most critical elements due to the new load path of lateral forces need to be considered carefully.

• Unnecessary repairing may produce more problems for structure than leaving it as is.

• Foundation rehabilitation for a new lateral load path is a major problem for already existing buildings.

An alternative solution is to perform a comprehensive column jacketing for a medium rise building that will not require any foundation work. However, it has a disadvantage that may reduce building space. Another solution is shear walls and bracing. However, the addition of shear walls mostly requires the addition of piles which is very difficult to perform.

• The cost of disrupting operations may be much greater than cost construction. Since occupancy may dictate the rehabilitation solution thus, a partial or full scheme shall be designed based on the cost optimization.

• The code does not distinguish between the designs of the new and existing structure as a result a large variation in ductility factor will take place.

• Documentation of rehabilitation case studies is needed for summarizing the techniques to be a guidance for other researchers.

3. RESEARCH SCOPE

The main objective of this research is to formulate Guidelines for Multi-disciplinary rehabilitation projects. The summarization of main disciplines studied in this research are Energy and structural building optimization are shown in Figure 3. A check list and guidelines will be formulated as a guidance for new projects combining structural and energy retrofitting.

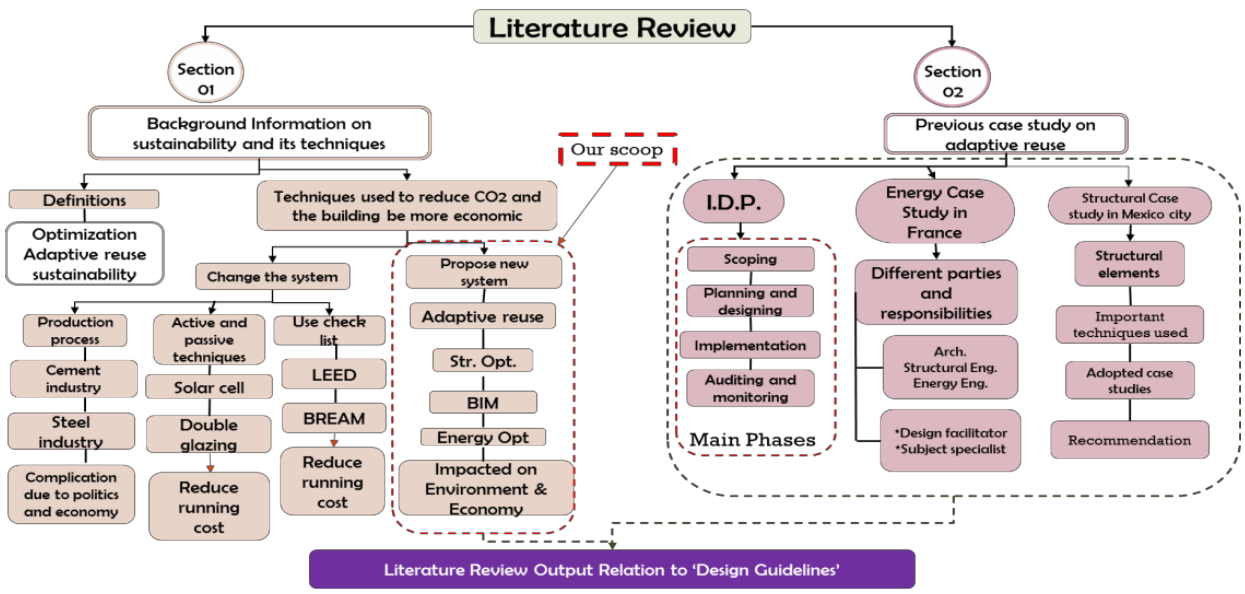

Fig. 3: Literature review summary.

4. METHODOLOGY

Three main perspectives (Structure optimization, Building Information Modelling and Energy Sustainability)

are discussed in detail in the literature review section. As a result, a formulation of preliminary integrated check list and guidelines are proposed, where the literature review considered the main reference for the checklist and the case studies for the phases and sequence identification.

5. ANALYSIS AND RESULTS

5.1. Preliminary check list and guidelines for evaluating an optimized building

According to the literature, preliminary guidelines are developed to cover multi-disciplinary optimization. The guidelines are stated as follows:

1- Many parameters need to be identified such as year, area, value of renovation cost and building type. If acommercial building is constructed after 1948 and greater than 1000 m^2 and its renovation cost is more than 25% of the building value, its overall consumption must be reduced by 30%[4,14,6].

2- Occupant activities along with systems used such as lighting and envelope information are effective parameters that need to be considered, collected, and documented [14].

3- If the light system installed in a building is older than 25 years, it's much recommended to update it as it will be of high saving potential[6].

4- Retrofitting schemes and recommendation need to be implemented according to the following parameters: expenses, defects, feasibility, and timeline.

5- As a result of disciplinary combination, some limitations occurred to meet the previously mentioned parameters. for instance, column jacketing approach

6- Regarding structural optimization, column jacketing technique is most appropriate to be implemented along with energy retrofitting.

7- Checking the vacancy of the building and deciding the cost optimization for the best energy and structural retrofitting schemes (Heavy, Light or In-use retrofitting scheme).

5.2. Building Optimization Sequence Matrix

From the previous literature, guidelines are proposed and accordingly a sequence and responsibility matrix are driven to facilitate the process of applying those guidelines on any case study to meet the multidisciplinary optimization approach. The Guidelines matrix is composed of three parameters (The Horizontal axis is the energy optimization) and the vertical axis (the architectural and structural optimization) thus the three parameters are linked as shown in Figure 4.

6. CONCLUSION AND RECOMMENDATIONS

From the previous data collection, it is found that retrofitting of structures is a more effective approach due to its high sustainable impact compared to other approaches. Thus, this research aimed to develop an integrated workflow between multi-disciplinary approaches adopting Structural Retrofitting & Energy Retrofitting to formulate a new sustainable guideline. These formulated guidelines are the main key to getting an in-depth analysis of the construction scenarios and identifying proper strategies to improve the energy efficiency and environmental impacts of buildings.

A matrix shown in Figure 5 is created and compiled, using these guidelines, to clarify the building optimization sequence concerning multidiscipline approaches and teams who are involved in such applications. As a result, every member according to his/her specialty will be able to use this sequence matrix in any multi - disciplinary future work to reach the most optimum sustainable solution for the old and refurbished structures. These guidelines and matrix created need to be validated using the applied case study. The case study will be a prototype model adopting some key parameters.

6.1. Future Work

Continuation of this research by applying the guidelines on the case study mentioned previously. The analysis will be conducted using BIM (Autodesk Revit) and energy simulation software (Design Builder). The case study key performance index will be composed of two parameters regarding structure optimization and energy optimization respectively, for the first it will be the building stability and safety, the second one will be the amount of saved energy before and after its optimization.

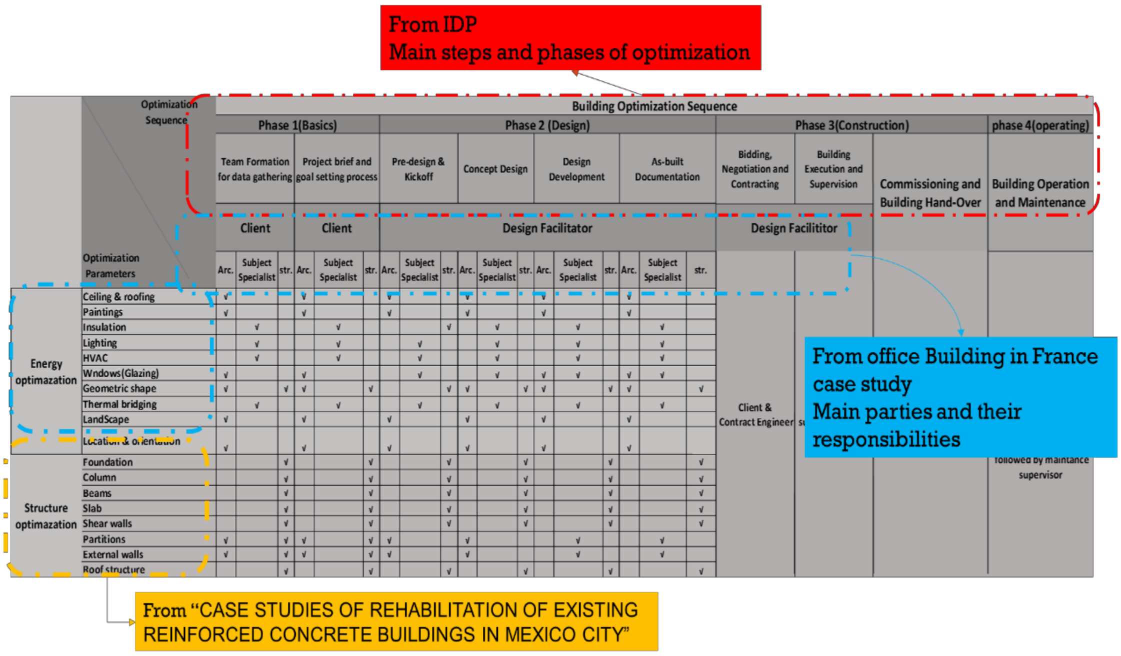

Fig. 4:. Responsibility Matrix sequence reference

Optimization Sequence / Optimization Parameters		Building Optimization Sequence																	
		Phase 1(Basics)						Phase 2 (Design)											
		Team Formation for data gathering			Project brief and goal setting process			Pre-design & Kickoff			Concept Design			Design Development			Building Documentation		
		Client			Client			Design Facilitator											
		Arc.	Subject Specialist	str.	Arc.	Subject Specialist	str.	Arc.	Subject Specialist	str.	Arc.	Subject Specialist	str.	Arc.	Subject Specialist	str.	Arc.	Subject Specialist	str.
Energy optimazation	Ceiling & roofing	√			√			√			√			√			√		
	Paintings	√			√			√			√			√			√		
	Insulation		√			√				√		√			√			√	
	Lighting		√			√			√			√			√			√	
	HVAC		√			√			√			√			√			√	
	Windows(Glazing)	√			√				√			√		√	√		√	√	
	Geometric shape	√		√	√		√			√	√		√	√		√	√		√
	Thermal bridging		√			√			√			√			√			√	
	LandScape	√			√			√			√			√			√		
	Location & orientation	√			√			√			√			√			√		
Structure optimazation	Foundation			√			√			√			√			√			√
	Column			√			√			√			√			√			√
	Beams			√			√			√			√			√			√
	Slab			√			√			√			√			√			√
	Shear walls			√			√			√			√			√			√
	Partitions	√		√	√		√	√			√				√			√	
	External walls	√		√	√		√	√			√				√			√	
	Roof structure			√			√			√			√			√			√

Phase 3(Construction)			phase 4(operating)
Bidding, Negotiation and Contracting	Building Execution and Supervision	Commissioning and Building Hand-Over	Building Operation and Maintenance
Design Facilititor			
Client & Contract Engineer	Str. & subject specailist	client & Design Facilitator	Architect & Energy advisor → followed by maintance supervisor

Fig. 5: Building Optimization Sequence and Responsibility Matrix.

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