OPTIMISING FLOOR SPACE DURING RETROFITTING OF HIGH-RISE OFFICE BUILDINGS

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A need for an efficient decision support tool for planning of office building refurbishment is emerging due to the significant increase in the number of ageing buildings in the world. In order to meet this need, all the aspects of building refurbishment projects such as waste minimisation and management, structural strengthening and floor space optimisation, estimation of residual life and construction management issues need to be integrated. Whilst there are number of such tools reported in the literature to cover other parameters in relation to re-life of buildings, they do not include evaluation of the optimising of rentable floor space and corresponding structural strengthening needs. This paper discusses the methodology for development of decision support frame work to compare and assess options available to the design team of a re-life project in optimising rentable floor space. The issues to be addressed during floor-space optimisation have been identified and prioritised through a Delphi process. These issues are then mapped against the life cycle of a refurbishment project and consolidated. Decision tool developed as a matrix to map existing as well as innovative structural strengthening techniques to strengthening needs is presented to demonstrate the application of the proposed model.

Key Words: Retrofit, Office buildings, Structural strengthening

1 INTRODUCTION

The significant growth in the construction of new commercial office buildings over the past 30 years has left a large stock of ageing buildings. The repair and maintenance expenditure of aged buildings is expected to increase due to the structural deficiencies and functional obsolescence. In such situations, the owner of a building has to decide the most judicious moment to undertake refurbishment to extend useful life of their buildings and improve their overall value or to replace them with a new building.

Over the past 5 years, an increasing number of projects are exploring the advantages of retrofitting of aged buildings and therefore, office building retrofitting market has seen considerable growth. The followings explanation of this paradox is given in Literature [1]:

- the life span of office buildings is much shorter than residential buildings;
- users' requirements have considerably changed in terms of office equipment, communications, automation, quality of use and comfort;
- buildings that do not offer all the amenities for comfort and flexibility are difficult to sell or rent;
- retrofitting a building costs much less than demolition and reconstruction;
- office buildings are classified amongst the buildings presenting the highest energy consumption.
- With the changes in legislation, approval of a new development of the same user capacity may not be permitted within the envelop of the old building

In developing a strong business case for re-life rather than demolition and re-build, a major issue to be addressed is maximizing of rentable floor space, which often puts a re-life project at a disadvantage. In increasing usable floor space, options available to the client include removal or adding floors and partitions, relocating services, cutting openings or extending floors and relocating lift wells etc. In each case, innovative strengthening schemes have much to offer when considering upgrading of the existing structure.

For a retrofitting project to be successful, the owner has to establish a suitable retrofitting plan of action. If a client makes inappropriate choices, the outcome may be a time and/or cost overrun and general dissatisfaction. Nowadays, a number of decision support tools are available to the owners to assess the current condition of their buildings with respect to deterioration, functional obsolescence, energy consumption and environment quality, before making a decision to retrofit their buildings. Those decision support tools also help to choose appropriate retrofitting actions and to estimate the cost. However, the available decision support tools do not cover the building structure. Consequently the “Floor space optimisation” strand of Re-life project funded by CRC for construction innovation is looking into the development of a management decision support tool that assists the owners in selecting an appropriate strengthening scheme during optimizing of floor space in a re-life project.

2 OPTIMIZING OF FLOOR SPACE DURING RETROFITTING OF BUILDINGSS

It is a significant challenge for engineers to satisfy the clients’ requirements during retrofitting; specially optimizing the usable floor space. Usable floor space of existing building can be optimized by modifying the layout of an existing building such as removing or adding of floors and partitions, relocating services, cutting openings or extending floors and relocating lift wells etc. In these situations, innovative structural strengthening schemes could be implemented to strengthen the existing structure. Strengthening of an existing structure may also become necessary under the following circumstances:

1. When buildings are exposed to harsh environments such as de-icing salts, chemicals or air-borne salt spray, or have inappropriate details, the structures may experience significant deterioration in the form of steel corrosion, concrete cracks and spalls [3]. Such deterioration may result in structural inadequacies that adversely affect the structure or its members,
2. In situations where the building owners make decision to change the usage of a type of building depending on the business demand in the current market environment. As a result, the existing structure of a building may or may not be strong enough to withstand the new loading,
3. Structures constructed in early days may have been designed to carry loads that are significantly smaller than the current needs, possibly due to increase demand usage [3],
4. Structural inadequacies may arise due to errors in initial design or construction and changes of design standards.

By carefully implementing appropriate structural strengthening methods, re-life of buildings can be justified/achieved rather than adopting demolishment and re-building

3 STRUCTURAL IMPLICATIONS OF OPTIMISING USABLE FLOOR SPACE

In situations where the use of the office floor requires changes to services such as lift wells air ducts, ventilation, lighting and the type of loads applied on it, load transfer mechanism of the building structure may require strengthening or re designing and re-building.

Selection of an appropriate strengthening method is dependent on the materials of construction. Structural elements of existing buildings are commonly constructed of concrete, steel, timber and masonry. Concrete is the most commonly used building material and widely used in the forms of in-situ concrete, precast concrete and post-tensioned concrete.

The structural strengthening can be achieved by section enlargement, external post tensioning, external bonded steel elements, bonded advanced fiber reinforced polymer (FRP) composites, span shortening, or a combination of these techniques [2,3,7,9,12-26]. No matter what strengthening technique is used, the ability to perform as an integrated system can be obtained only by providing an adequate bond between the existing member and the repair/reinforcement to ensure monolithic structural behaviour [2]. Stress concentrations resulting from added material should be investigated as they may cause a localized failure.

Unfortunately, there is no specification or design that covers all repair/upgrade scenarios and engineers, architects, and contractors must be innovative and thorough, in their design details, specifications, and applications.

4 MANAGEMENT SUPPORT TOOLS AVAILABLE FOR RE-LIFE PROJECTS

A good retrofitting action plan will lead to the success of a re-life project. With the aid of decision-making tools, it is possible to select the most suitable retrofitting action [3, 4, 5, 27, and 28]. A number of such tools have been developed for office buildings with TOBUS, MEDIC, EPIQR and INVESTIMMO being the most commonly reported in the literature [3, 4, and 5].

The decision-making software tools, EPIQR (for apartment buildings) and TOBUS (for office buildings) have been developed for the assessment of retrofitting needs of buildings in European countries. The use of these tools can facilitate a quick and accurate diagnosis of the condition of the existing building in terms of its major area including construction, energy performance, indoor environmental quality, and functional obsolescence. The main advantages of using these tools are the ability to evaluate various refurbishments and retrofit scenarios, and cost of induced works, in the preliminary stages of a project [1, 6].

In EPIQR and TOBUS, deterioration of building materials and components are described by the use of a classification system with four classes. The prediction of the period of passing into the next deterioration state is of high interest as this is directly connected to higher refurbishment costs. The prediction of qualitative deterioration states are important and correspond to key moments in the element's life where some refurbishment action has to be taken [1,6].

European countries have used another software tool entitled MEDIC to predict the future degradation state of building. MEDIC is intended for use with EPIQR and is based on a subdividing of the building into 50 elements. MEDIC calculates the remaining life span of a building element not as a deterministic unique value but as a probability distribution. It can help the owner of a building to decide the most judicious moment to undertake refurbishment to achieve his short and long term financial needs [3, 8, and 29].

Following the footsteps of EPIQR an TOBUS, a decision-making tool for long term efficient investment strategies in housing maintenance and refurbishment – INVESTIMMO has been developed in European countries. It has been aimed at evaluating housing maintenance and refurbishment options, which covers expectations of tenants, housing market, and quality of building upgrading and environmental impacts in addition to the factors identified in TOBUS [6].

From the review of literature, it was clear that these tools can be used to evaluate the general state of buildings with respect to some of the aspects of building re-life projects such as service life, functional obsolescence, energy consumption and environment impacts. However, no reported work presents a decision support tool, which can be used to compare and assess options available to the design team of a re-life project in optimizing rentable floor space.

5 INTEGRATED FRAMEWORK FOR DECISION MAKING

In order to develop a decision support tool for selecting the most appropriate structural strengthening scheme during optimizing of floor space, the preliminary objective was to identify the clients' requirements and problems associated with structural strengthening. Through the review of literature and based on the experience, a list of issues, which may influence strengthening work has been compiled. Consequently, Delphi process was utilised to rank them based on the importance in refurbishment projects [10, 11]. The following issues were identified as important by the experts engaged in research/practice in the field of building refurbishment:

1. change of use of floors,
2. cutting openings in floors and extending floors,
3. relocate/renew services,
4. structural appraisal prior to refurbishment and
5. safety reliability issues in structural strengthening.

The next challenge faced by the research team was integrating the issues specific to structural strengthening with other issues such as construction management, estimation of the residual life and managing waste and recycling. This was achieved by mapping the issues against the project life cycle as shown in Figure 1, established through an industry workshop with the partners of the project. This identified the input parameters required at each stage of the project life cycle. In this paper we are focussing on the floor space optimisation and structural strengthening during building refurbishment. Detailed mapping of issues to different phases of the project are captured in Table 1.

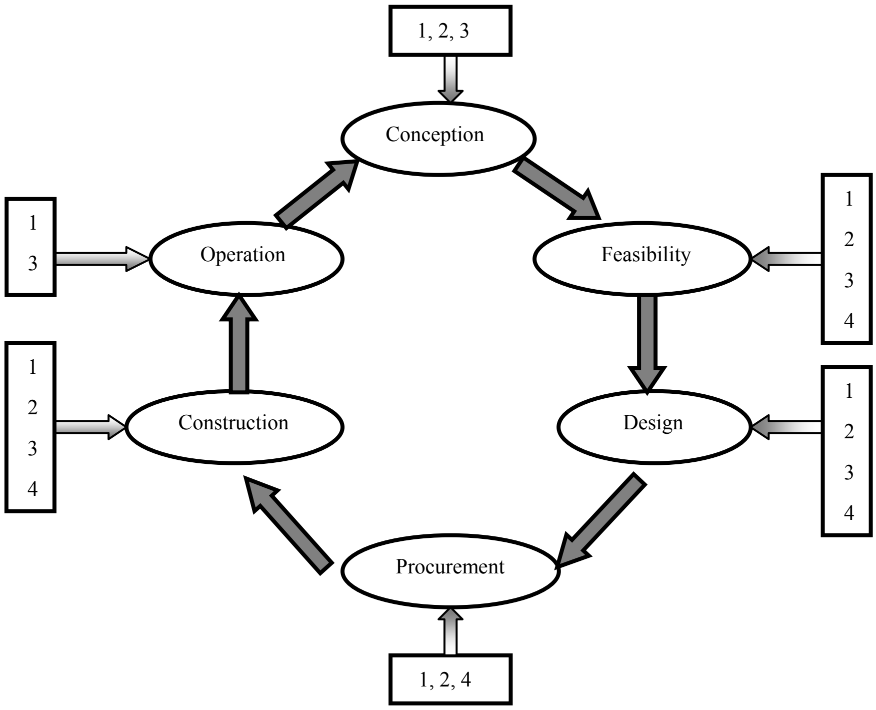

Figure 1: Life cycle of a building refurbishment project

Where 1, 2, 3 and 4 are the inputs from main aspects of building refurbishment projects

1–Construction management issues, 2–Structural strengthening and floor space optimisation, 3–Estimation of residual life, 4–waste minimisation and management.

Phases of life cycle of a building / Issues Associated with optimising floor space and structural strengthening	Conception	Feasibility	Design	Procurement	Construction	Operation
Structural Appraisal	√	√	√			
Change of use of floors	√	√	√			
Relocate/renew services	√	√	√	√	√	
Impact on structural strength		√	√			
Safety issues for structural strength		√	√			
Cutting opening/extending floors			√		√	

Table 1: Mapping of floor space optimisation issues to different stages of the project life cycle

6 INPUT PARAMETERS TO THE LIFE CYCLE OF BUILDING REFURBISHMENT

Expanding the issues presented in table 1, researchers identified detailed decision parameters required at each phase of the project life cycle to achieve an optimised solution for usable floor space. These were identified through extensive industry consultation complemented by a review of published work. Decision parameters are given in Table 2. For example, at the project conception stage most important parameters are remaining life of the building, structural capacity of the existing building, and structural constraints in the existing building such as flexibility in altering the structure, changes to loads or load transfer mechanisms and structural requirement in relocating services. These issues are identified by studying in-detail the refurbishment reports of two case-study buildings: Council House 1 of Melbourne City Council (CH1) at little Collin Street in Melbourne and Health building at George Street in Brisbane. The two case study buildings covered two distinct refurbishment scenarios. CH1 building refurbishment was driven by a need to arrive at 6-star energy rating to match that of the adjacent council building CH2 which is a state-of-the-art green building. This required drilling through the flat slab floor to relocate services, opening up of light wells to improve natural lighting and ventilation and changes to the windows. George St. building in Brisbane has utilised a concept of integration of two adjacent buildings to optimise the floor space. Through the integration, floor space has been optimised by removing two sets of service cores and demolishing a stair well and using a common lift lobby. For both case study buildings the evaluation methodology for the parameters given in table 2 has been compiled by the research team. This information can be presented as a decision support tool, which will allow the project team to establish typical values for each of the parameters and ascertain the feasibility of a given floor space optimisation option. A typical example is given in table 3 and explained in section 7.

Phases of life cycle of a building	**Parameters to be considered developing guide lines for optimising floor space and structural strengthening of a building**
Conception	● remaining life of the existing building ● structural capacity of the existing building ● structural constraints ● change in load conditions ● change in load transfer mechanisms ● possible options for floor framing and relocation of services ● services to be considered for relocating or renewing ● structural requirements to support relocation of services
Feasibility	● cost of different structural treatment options, floor framing and relocating/renewing services ● availability of technology and expertise for structural appraisal, change of use of floors and relocate/renew services ● reliability of structural appraisal ● environmental issues on structural appraisal and change of use of floors ● user comfort due to relocate/renew services ● consider innovative options for relocating/renewing services ● integrate or evaluate structural options with other issues ● structural safety margins
Design	● calculation of residual structural capacity of existing building ● specialist evaluation techniques ● calculation of structural capacity with new loading condition ● consider innovative options for relocating/renewing services and cutting openings/extending floors ● consider all possible safety requirements ● consider floor framing option which has a relatively low effect on overall structural strength
Procurement	● availability of expertise for relocating/renewing services ● Availability of expertise for structural strengthening ● contractual terms for relocating/renewing services ● reliability of relocating/renewing services
Construction	● proper planning of relocating/renewing services ● techniques adopted for cutting opening/extending floors ● Structural strengthening
Operation	–

Table 2: Parameters to be considered in developing guidelines for optimising floor space and structural strengthening of a building

Structural Strengthening Solutions	Application Projects	Characteristic	Possible Applications	Issues Associated with the solutions	Companies/Contractors
1. **Externally bonded composite system** **- Fiber Reinforced Polymer (FRP)** **- Hardwire® Steel Reinforced Polymer (SRP)**	• Utility tunnel at a University in South Florida • Restoration of swimming pool roof structure, Kalmthout, Belgium	• speed and ease of installation • lower cost • aesthetic appeal • light weight • non-corrosive • excellent fatigue behaviour • non-conductive • can be used for flexural, shear, and axial (confinement) upgrading and crack control • due to thin profile, r/f can be easily run in two directions for two way slabs • allow for carpet, tile, and other flooring finishes to be installed over the system without any significant change in floor elevation	• concrete slab, beam, column and wall • wooden beam, column • masonry	• can damage the externally bonded composite • problematic in flooring applications when used on cracked concrete slabs as these cracks may allow reflective cracking throu' polymer topping.	• VSL International Ltd • Structural Preservation System (USA) • Edge Structural Composites (USA) • C.A. Lindam Companies (USA) • Watson Bowman Acme Corp. (USA)
2. **Section Enlargement**		• relatively easy method • not good in harsh environment. Possible corrosion of embedded reinforcing steel. • can increase load carrying capacity or stiffness • additional concrete can be placed in the form of an overlay or jacket	• concrete columns, beams, slabs	• Increase the weight of existing structure. weight can be minimised	• VSL International Ltd • Structural Preservation System (USA)
3. **External Post-tensioning**	• Two-span steel truss bridge (48-48m) over River Aare at Aarwangen, Switzerland • Pier 39, Parking Structure San Francisco, USA • Double-tee stems on an overpass located on the premises of a University in Washington. Damaged due to overheight truck.	• Possibility of controlling and adjusting the tendon forces, inspecting corrosion protection and replacing tendons. • can be used for both reinforced and prestressed concrete • minimal additional weight to the repair system • ecconomical • requied less time to complete • can be used for flexural , shear and axial (confinement) upgrading	• Applicable for structural steel, composite steel-concrete, timber and masonry structures. e.g. building with masonry walls, girders in buildings, roof structures, circular structures such as silos, reservoirs and large masonry chimneys. • great success to correct excessive deflections and cracking in beams and slabs, parking structure and cantilever members. • due to minimal additional weight of repair system, this is effective and ecconomical for long span beams • existing concrete structures against fatigue and cracking	• vulnerable to corrosion, fire and vandalism. However, improved ductility & fire proofing can be achieved by placing reinforcement in ducts that can grouted after stressing of tendon. Protection can also be achieved by encasing the post tensioning system in concrete or by using shotcrete. • Externally bonded bars can be damaged by traffic. However, that can be prevented by installing the system in grooves made in existing member. • requies access to sides and sometimes ends of member	• VSL International Ltd • Structural Preservation System (USA) • C.A. Lindam Companies (USA)
4. **Bonded steel element**	• Quatier des Celestines, a 19th century building in Namur	• Steel element can be steel plates, channels, angles or built-up members • steel elements can be bonded with epoxy adhesive. In addition to epoxy, mechanical anchors can be used to ensure steel element will share loads in case of adhesive failure. • can improve shear and flexural strength	• Steel plate bonded to tension face of concrete beam can increase flexural capacity, flexural stiffness and in deflection and cracking decreases • Steel plate bonded to side of the member can improve shear strength of concrete beam. • install structural steel beams on the underside of structures and steel brackets at column heads. • long-term solution for structures subjected to aggressive environment	• influence to corrosion and fire.Suitable corrosion protection system and fire protection system can be used. • due to their restrictive length, steel elements need to be spliced which complicate the design and construction operation • existing reinforcement can be damaged while placing the anchors. Considerable site work is required to accurately locate existing reinforcement. • Expensive false work is required to maintain the steel work's possition during bonding. • Adding strengthening material under existing structure may redue the usable headroom	• VSL International Ltd • Structural Preservation System (USA) • C.A. Lindam Companies (USA)

Table 3: Matrix of mapping solutions to problems (Contd.)

Structural Strengthening Solutions	Application Projects	Characteristic	Possible Applications	Issues Associated with the solutions	Companies/Contractors
5. **Span Shortening**	• Shortened span in Parking Garage	• reduce the force in overstressed beam • increase the load carrying capacity • best material for this application is steel, which is quick to install.		• result in loss of space and reduced headroom. • New footing for new column is expensive less expensive approach is to install diagonal braces that extend from the bases of existing columns	
6. **Hybrid strengthening method** eg. steel/CFRP	• Strengthening of a roof system of an elementary school in New Jersey. They wanted to install skylight on existing roof slab. • Transformation of former school building to library • Roof structure of warehouse at Brussels in Belgium (due to calculation error,capacity of main supporting beams are not suficient)	• less expensive • aesthetically pleasing • fast application	• slab with opening • rib slabs		• Structural Preservation System (USA)
7. **Removing existing concrete and casting with lightweight concrete overlay (with steel wire mesh or steel bar)**	• Baltimore's historic Hippodrome Theater renovation -France	• increase bending capacity by increasing effective depth of existing bottom r/f • at support, embedded steel steel r/f in overlay increase the bending capacity • r/f in overlay limits cracking of overlay	• concrete slab and beam	• adequate surface preparation is required to ensure the bond between overlay and existing structure • overlay replace existing topping and therefore small increase in dead load, which offset by using lightweight concrete.	• Structural Preservation System (USA)
8. **Hardwire**	• Baltimore's historic Hippodrome Theater renovation -France	• hardwire made of ultrahigh strength steel wires twisted together to form reinforcing steel cords wires bonded to existing structures with epoxy adhesive • hardwire works as additional r/f to provide tensile strength	• reinforced and prestressed beams, girders, and slabs to provide additional flexural strength. • can be used on sides of beams and girders to provide additional shear strength. • can be used on structural elements to increase their capacity.		• Structural Preservation System (USA)
9. **Hardwire steel belt with polymer flooring system**	• Leading national home improvement warehouse • multi-story warehoue/ distribution facility for a large automative parts distributor in illionis	• hardwire does not replace today's polymer flooring system. However, additon of hardwire dramatically strengthens retrofitflooring design capabilities. • combination of polymer flooring with these thin steel belts creates a system with the ability to increase structural capacity, blast resistance and general toughness of concrete • ability to integrate with multiple polymer and cementitious materials	• heavy trafficked warehouses, manufacturing slabs, elevated slabs, slabs on pile construction, and slabs that are structurally deficient from improper design or construction • viable solution where emission and odors are an issue.		• Structural Preservation System (USA)
10. **Replacing existing wire system with encapsulated monostrand post tensioning system**	• Parking Garage in New York	• existing structure to be post tensionned system • time and cost effective			• Structural Preservation System (USA)
11. **Epoxy mortar**	• Timber floor in a castle	• can be used to strengthen old timber structures. excellent material to repair wood because it has strong bond to wood and MOE is nearly equal to wood.	• Timber - A large groove was sawed on top side of the beam. Steel r/f has been placed in these groove. Then grooves are filled wth epoxy mortar.		

Table 3: Matrix of mapping solutions to problems

7 EXAMPLE OF A DECISION SUPPORT MATRIX FOR STRUCTURAL STRENGTHENIGN ISSUES

Table 3 demonstrates a typical matrix developed to provide decision support for structural strengthening issues at the conception and feasibility stages of a re-life project. The matrix covers possible structural strengthening solutions, typical application projects, characteristics of the strengthening method, possible applications and issues and the local expertise availability for a typical scheme. This allows the project team of a re-life project to identify possible strengthening solutions and feasibility of these prior to engaging a consultant for a specific issue. The complete tool covers other information such as typical costs and sample calculations for a typical strengthening solution. This matrix has been calibrated using data from the two case study buildings mentioned earlier: CH1 building in Melbourne and 63 George St. Building in Brisbane [30]. Similar matrices are currently being developed to cover parameters identified in table 2 such as options in improving energy rating using relocation/renew services, façade and window treatment and improved ventilation, integration of structural issues with other issues such as waste minimisation and construction and procurement methods.

8 CONCLUSIONS

The paper presented the challenges faced by engineers in decision making during re-life of buildings. It then presented a methodology for identifying major issues affecting optimisation of floor space and structural strengthening of buildings during a refurbishment project. A method for mapping major issues identified as influencing re life of buildings to different stages of the project life cycle has been presented. This model presents decision makers with valuable guidance at different stages of the project life cycle of a re-life initiative. An example of a detailed decision support guideline developed to cover one major parameter has been presented to demonstrate the application of the model. This guideline given as a matrix in table 3 has been validated with data from two case study buildings and other published work.

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