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Applications of the Open Building Renovation System and BIM Technology in the Sustainable Renovation of Existing Apartment Buildings in Taiwan

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ABSTRACT ‘Apartment building’ has been the major type of habitat in metropolitan areas in Taiwan, and the majority of existing apartment buildings are more than 30 years old now. Many problems have appeared in these old existing apartment buildings, and the renovation of these buildings becomes extremely difficult and has become a critical yet troublesome issue for owners. The ‘open building’ concepts and ‘building information modeling (BIM)’ techniques are adopted to resolve the problems of sustainable renovation of old existing apartment buildings. Firstly, the ‘open building renovation system (OBRS)’ was developed to be adopted to renovate and sustain existing apartment buildings. The OBRS consists of five subsystems: (1) floor subsystem to be placed on existing RC slab to form a coordination reference system to integrate the partition base subsystem, pipelines and wire; (2) partition base subsystem highly integrated with floor subsystem, pipes and wire, and conventional partition products; (3) door frame subsystem; (4) sandwich wall panel subsystem to be added on existing RC wall to protect the existing wall; (5) aluminum window subsystem integrated with exterior wall subsystem and interior partition product to protect existing walls and form a new water-proof envelope. The OBRS is then applied in a 3BR apartment unit (90m²) within an existing apartment building as a case study to simulate and demonstrate the interior design and renovation construction processes over a thirty-year period, and life cycle cost analyses performed. It’s revealed that the first cost of the OBRS is 30% higher than that of the conventional system in the first renovation, and 30~40% lower in the subsequent renovations; and the higher first cost of the OBRS can be paid back in the third renovations. Finally, building information modeling (BIM) techniques were applied in the study case to explore the potential benefits or difficulties of BIM applications in building renovation projects.

KEYWORDS: support, infill, maintainability, systems integration, life cycle cost

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Kung-Jen Tu is an Associate Professor in the Department of Architecture, National Taiwan University of Science and Technology. Currently, he also serves as the Secretary General of the Taiwan Institute of Property Management. He specializes in the areas of ‘open building design’ and ‘facility management’. His research focuses on adopting ‘open building’ as an effective building design strategy in offering flexible building infrastructure to improve building maintainability, to accommodate diverse spatial needs and to allow users to customize their space.

Shih-Kahn Chu is a registered architect in Taiwan. He was an Adjunct Assistant Professor in the Department of Architecture, National Taiwan University of Science and Technology. He specializes in the areas of ‘open building’, ‘architectural design’ and ‘interior design’. He has been involved in several government-funded open building research projects in the past few years, in which he developed open building prototype designs for the ‘support’ of public housing and private apartment buildings, as well as ‘infill parts’ for sustainable renovations of existing apartment buildings in Taiwan.

1 Introduction

‘Apartment building’ has been the major type of habitat in metropolitan areas in Taiwan, and 50% of them are more than 30 years old now (Lin and Liang 2006). Certain conventional construction practices in apartment buildings have affected the spatial functionality and maintainability of apartment units required in order for the building to meet households’ changing needs and to sustain over its life span. For example, main pipes in
bathrooms are typically placed within enclosed vertical shafts, and branch pipes and wires buried within columns, walls and slabs (Fig. 1a, 1b), making it difficult to maintain, repair or renew pipes and wires (Cheng 2001). In addition, conventional brick partitions have made it difficult to reconfigure interior layout of apartment units, and generated large amount of construction waste and noise during renovation (Figure 1c). As a result, it is common for individual households to customize and renovate their units by adding external pipes and wires on building façade haphazardly, resulting in chaotic building appearance (Fig. 1d, 1e). The average life span of domestic residential buildings is only 30-year in Taiwan (Chen and Lin 2001), meaning that most of the existing apartment buildings are old and deteriorating, and will soon be demolished if no appropriate renovation systems are developed to extend their life spans.

To resolve the above problems, this study applied ‘open building’ concepts and techniques to develop the ‘Open Building Renovation System (OBRS)’ to be adopted when renovating existing apartment buildings to improve their flexibility, maintainability, and sustainability.

Building information modeling (BIM) is a process involving the generation and management of digital representations of physical and functional characteristics of places. BIM is a new technique receiving great attention in the construction industry worldwide and its applications in the design and construction phases of ‘new building project’ have been the focus of major research effort (Eastman et al. 2008). This study intends to further explore its potential applications and benefits in the renovation of ‘existing buildings’.

Fig. 1. Conventional construction practices of pipeline distributions in bathrooms (a, b) and interior brick walls (c), as well as the housing customizations conducted by the occupants on building facade (d, e).

2 The ‘open building’ concept

‘Open building’ is a design concept and approach aiming to deliver buildings with maximal capacity for accommodating the diverse needs of different householders over time. To achieve such goals, Habraken (1976), the pioneer of open building theory, proposed that the following building delivery process and supply chain model be established:

1. The making of a building is divided into two stages: the ‘support’ of a building (base building elements with longer lives and remain unchanged, such as structure, envelope, etc.) and the ‘infill’ (fit-out elements with shorter lives and change more often, such as partitions, floors, equipment, service pipelines, cabinets, etc.).
2. The ‘support’ of a building is designed to form a flexible and open architecture to accommodate diverse ‘infill’ parts. Systematic design methods, such as the SAR method devised by Habraken (1976), may be applied in the design of the ‘support’.

3. An ‘infill’ industry is formed to supply diverse ‘infill’ systems and parts that are highly integrated or interconnected, and can be independently installed or upgraded within an open architecture (support) for each household.

‘Open building’ has been implemented worldwide in the making of new residential open buildings (Kendall and Teicher 2000). Its implementation in Taiwan was first realized around 2010 by the SUNTY Development’s S/I new housing projects based on Japanese experience. For the majority of existing apartment buildings in Taiwan, the concept of ‘open building’ was not implemented, and the ‘support’ of these buildings were not designed to be as open and flexible as expected. To make existing apartment buildings more sustainable and long-lasting, this study focused on developing an open interior ‘infill’ system and components to be applied and simulated in housing renovation, based on research projects supported by the Architectural and Building Research Institute (Lin et al. 2009; Tu et al. 2014).

### 3 The Open Building Renovation System (OBRS)

By adopting ‘open building’ concepts, the ‘Open Building Renovation System’ (OBRS) was developed to be a universal solution to meet the housing renovation needs of any householder in any phase of building life in any type of apartment product in Taiwan. The OBRS intends to achieve maximum ceiling height and spatial flexibility, minimum material consumption and construction waste, and integration for wire and pipe management in each renovation project. The developed OBRS consists of five major subsystems (Fig. 2):

1. **Floor subsystem (Fig. 2a):** Modular floor tiles (30cm*30cm; 9cm thick; with 3cm wide fillisters 15cm apart) made of high density polystyrene are placed on existing RC slab to form a coordination reference system to integrate the partition base subsystem, pipelines and wire. Finished wood flooring and plywood base are then placed on top of the modular floor tiles. In the wet space such as toilets, two layers of modular floor tiles may be used to accommodate the required slope of waste water drainage pipes. The concept of modular floor tiles is borrowed from the Dutch MATURA infill system (Kendall and Teicher 2000).

2. **Partition base subsystem (Fig. 2b):** 6.5cm thick and 12cm high wood plastic composite blocks with four different widths (11.75~30cm wide) are devised to be inserted on modular floor tiles to form the bases to support interior partitions. 2mm thick galvanized steel plate is bended to form metal channel units (6.5cm thick, 30cm wide, 30cm high) for distributing power and communication wires. The metal channel units are placed on top of the wood plastic composite base to support existing light gauge steel frame partition systems. Metal partition base subsystem highly integrated with floor subsystem, pipes and wire, and conventional partition products. The partition base subsystem integrates the components of the floor subsystem and existing interior partition subsystems.

3. **Door frame subsystem (Fig. 2c):** Vertical wood studs are carved to appropriate form to be connected to the fillisters of the modular floor tiles and the partition base subsystem (metal channel units and wood plastic composite base).

4. **Sandwich wall panel subsystem (Fig. 2d):** Light gauge steel C-channels (C100x50x20) are bolted onto the existing RC walls (with tiles) to form the support for the metal sheet wall panels (30cm wide, 5cm thick; cladding rock wool insulation). With open joint design, the upper metal sheet wall panels are stacked onto the lower panels, and vertical gaskets are placed between wall panels and sealant applied. The sandwich wall panel subsystem is a subsystem on the market to be adopted and integrated into the OBRS to protect the existing RC walls.

5. **Aluminum window subsystem (Fig. 2e):** After tearing down the existing aluminum window frames, two layers of aluminum window frames (external and internal) are devised to interlock to form a set of unified window frame, to protect the existing window opening, and to be integrated with the sandwich wall panels as well as the interior partitions.

Table 1 reveals the differences between the OBRS and the conventional construction system widely adopted in housing renovation in Taiwan. Essentially, the conventional construction system is regarded as ‘wet, enclosed and inaccessible’ construction, and is less flexible to meet occupants’ changing needs and is difficult to maintain. Whereas, the OBRS is regarded as ‘dry, modular, demountable and accessible’ construction, and
offers high level of spatial flexibility to cope with diverse customers’ needs over time, as well as maintainability.

Fig. 2. The five subsystems of the OBRS: (a) floor, (b) partition base, (c) door frame, (d) sandwich wall panel, and (e) aluminum window subsystems.

Table 1. Comparing the OBRS against the conventional system widely adopted in housing renovation.

<table>
<thead>
<tr>
<th></th>
<th>Exterior wall</th>
<th>Floor</th>
<th>Partition</th>
<th>Bathroom Plumbing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional system</td>
<td>RC wall with tiles</td>
<td>Tiles/stones on concrete slab</td>
<td>Brick wall</td>
<td>Embedded in brick wall or concrete slab</td>
</tr>
<tr>
<td>OBRS</td>
<td>Sandwich wall panels with steel studs</td>
<td>Modular floor tiles; finished wood flooring</td>
<td>Integrated and relocatable partition base, with typical light gauge steel stud partition system</td>
<td>Distributed in modular floor tiles connected to maintainable main vertical pipes</td>
</tr>
</tbody>
</table>
4 Housing Renovation Application and Life Cycle Cost Analysis

The developed OBRS was further applied in a realistic apartment unit to simulate a series of possible housing renovations during building life cycle and to analyze the resulting life cycle cost of the OBRS applications.

4.1 The Study Case

The research subject is a standard three bedroom apartment unit (90m²) within a thirty years old seven-floor apartment building (faculty dormitory) on a university campus in Taipei City (Fig. 3). The apartment building was built of conventional construction method and materials, such as RC walls with tiles, RC slabs with floor tiles, brick walls, and plumbing embedded in brick walls or RC slab, as indicated in Table 1.

![Fig. 3. The study case: a 3BR apartment unit within a seven-floor existing apartment building.](image)

4.2 Typical OBRS Application Process

The OBRS was applied in the 3BR apartment unit to simulate the following typical application process and tasks (not actually implemented and constructed), and the application results are illustrated in Fig. 4:

1. All the original partitions within the unit are first removed to uncover the bare ‘support’ of the unit;
2. The modular floor tiles are positioned and laid on the RC slab of the unit which forms a coordination reference system;

![Fig. 4. The results of OBRS application in the 3BR apartment unit study case.](image)
3. Interior partitions are placed along and on the inside of the perimeter wall;
4. Interior layout is reconfigured based on new spatial needs, and interior partitions placed along the grid line;
5. Two new vertical shafts consisting main plumbing and gas pipes are installed and attached to the balcony;
6. Two bathrooms are placed and configured adjacent to the new vertical shafts;
7. Horizontal pipes are distributed horizontally from both vertical shafts, through the modular floor tiles, and to the wet spaces (Fig. 4b);
8. Power and communication wires are distributed horizontally from the panel next to the entrance, through the modular floor tiles and metal channel units in partition base, to the outlets on interior partitions;
9. Light gauge steel C channels and metal sheet wall panels are installed on the surface of the existing RC walls, leaving the window openings uncovered;
10. Two layers of aluminum window frames are placed around the openings and interlock;
11. Metal frames are installed and connected to the light gauge steel C channels of the sandwich wall panels to support A/C units.

4.3 Housing Renovation Simulation during Building Life Cycle

The study case apartment building is 30 years old now. This study further simulates the OBRS applications to the 3BR unit at different time of its building life cycle to assess its performance in extending building life and to estimate the associated life cycle costs. The following three housing renovations at year 30 (current), 45 and 60 are simulated:

1. Renovation 1 (year 30, current): all the interior partitions in the 3BR unit are removed, and the OBRS subsystems are used to configure back to the original layout and to renovate the exterior walls of the unit. This renovation allows us to understand the first cost implications of the OBRS application.
2. Renovation 2 (year 45): the unit is reconfigured to a 4BR layout. Some portions of interior partitions stay and are re-used, whereas some demolished and replaced with new components. The exterior sandwich wall panels and aluminum window frames are renovated (assuming 30% demolished and replaced with new components).
3. Renovation 3 (year 60): the unit is reconfigured from 4BR back to the original 3BR layout. Some portions of interior partitions stay and are re-used, whereas some demolished and replaced with new components. The exterior sandwich wall panels and aluminum window frames are renovated (assuming 30% demolished and replaced with new components).

![Fig. 5. Three floor plans of the 3BR apartment unit reflecting three interior layouts resulting from three housing renovation at year 30, 45 and 60.](image_url)

4.4 Life Cycle Cost Analysis

Life cycle cost analysis was performed to compare the costs of the above three renovations between the OBRS and the conventional renovation system. Each renovation cost can be broken into the following categories:

1. Demolition cost: the cost to demolish and remove the non-reusable existing infill parts (finish floor, partition, ceiling, window frame, and exterior wall);
2. Floor cost: the cost to repair existing floors and construct new floors; to redistribute the wires and pipelines;
3. Partition cost: the cost to repair existing partitions and construct new partitions; to redistribute the wires and pipelines;
4. Ceiling cost: the cost to repair existing ceilings and construct new ceilings;
5. Envelope cost: the cost to repair existing exterior walls and construct new floor exterior walls.

The life cycle cost analyses reveal the following results (Fig. 6):

1. The costs of three housing renovations adopting the ‘conventional renovation system’ remain relatively steady, ranging from 375K to 466K NTD (New Taiwan Dollar). On the other hand, the renovation costs adopting the OBRS for the first time (renovation 1:614K NTD) is higher than those subsequent renovations which are relatively stable (renovation 2 & 3: 216K~288K NTD).
2. The first cost of the OBRS is 31.8% higher than conventional renovation system: The first renovation cost of the OBRS is 614K NTD (6,822NTD/m²) is higher than that of the conventional renovation system is 466K NTD (5,178 NTD/m²), mainly because of higher first cost associated with OBRS’s partition base and sandwich wall panel subsystems.
3. The subsequent renovation costs of the OBRS are 30~40% lower than the conventional renovation system: The second and third renovation cost of the OBRS are 288K NTD (3,204 NTD/m²) and 216K NTD (2,397 NTD/m²), whereas those of conventional renovation system are 415K NTD (4,608 NTD/m²) and 375K NTD (4,170 NTD/m²); mainly because of OBRS’s lower demolition, floor, partition, and envelope costs (Figure 5) resulting from the ‘reusability’ of the subsystems.
4. The accumulated total renovation cost of the OBRS is 11% lower than conventional renovation system: The accumulated total cost of the three renovations of the OBRS is 1,118K NTD (12,423 NTD/m²), whereas that of the conventional renovation system is 1,256K NTD (13,956 NTD/m²).
5. The higher first cost of the OBRS can be paid back in the third renovation: The OBRS’s accumulated life cycle cost becomes lower in renovation 3. The more often an unit is renovated during its life cycle, the more cost advantages the OBRS has.

![Graph showing life cycle cost analysis](image)

**Fig. 6. Life cycle renovation cost analysis: the OBRS vs. the conventional renovation system**

**5 Potential Applications of BIM in Open Building and Housing Renovation**

Building information modeling (BIM) techniques were applied in the study case to explore the potential benefits or difficulties of BIM applications in the renovation of existing buildings. BIM software REVIT was used to build the BIM model (LOD 200) for the apartment building study case and the 3BR unit (Fig. 7). Through the BIM explorations and exercise, this study found that, although may be more time consuming to build BIM models, BIM exhibits the following three potential applications in open building and housing renovations.
5.1 Organizing Support and Infill Components with Appropriate ‘Level’ Relationship

When establishing the BIM model of the subject building, components of the ‘support’, such as components of the structural system, envelope system, main pipes and wire in vertical shafts and service core are carefully built first. Then the components of the ‘infill’, such as OBRS subsystems (floor, partition base, door frame, sandwich wall panel, aluminum window frame) and other subsystems on the market (partition, horizontal pipe and wire, closet and cabinet, fixture and appliance, and furniture) are built. In REVIT, each system or subsystem is given a ‘family’ name, and the components of each system or subsystem are defined as various ‘types’ of elements under the same ‘family’. This study found it an effective way to group or organize building systems / subsystems and their components to establish appropriate ‘levels’ relationship among systems or components.

![BIM model](image)

Fig. 7. The BIM model of the apartment building study case built by the REVIT software.

5.2 3D Visualization for Design Schemes Review

Although not a brand new concept, this study found that the 3D images generated by the BIM model represent an effective way to convey designer’s concepts and design schemes for the client to perform design review in a renovation project. For example, 3D views of the whole apartment unit or a particular space in the unit can be presented and reviewed. In addition, it is an effective way to inform the client of the construction schedule or total construction time required by presenting a series of 3D images indicating the construction sequence of various OBRS subsystems (Fig. 8). Finally, the finalized BIM model can be passed on to the client as an updated as-built model for future reference in subsequent renovation projects.

In addition, this study finds it worthwhile to explore the potential application of BIM in ‘participatory design’ in renovation projects. With all the subsystems of OBRS and their components pre-defined, it is suggested that future research effort be dedicated to assess the possibility of allowing the client to explore different design ideas or customize a design scheme during a design review meeting, as well as to suggest the functions or system interface required.
5.3 Responsive Renovation Cost Estimation

When defining each component (type) of a OBRS subsystem (family) with the REVIT software, each component is also given a construction code (same as the code in CSI MasterFormat®), which is used to identify current construction unit cost for each component when linked to the PCCES (Public Construction Cost Estimation System) system developed and updated by the Public Construction Commission (a government agency). In the 3BR renovation project, the REVIT software can produce a ‘bill of quantities’ (itemized material, parts, and labor based on the design scheme) in a timely fashion. As a result, total construction cost or itemized construction costs of all subsystems can be estimated in a rather responsive matter. This study found that BIM technique represents an effective decision support tool allowing the client to facilitate or finalize design decisions when exploring alternative design ideas or schemes in a design review meeting.

Fig. 8. 3D images showing the construction sequence of the components of various OBRS subsystems in the 3BR unit renovation project.

6 Conclusions

The ‘open building’ concepts were adopted to develop the ‘Open Building Renovation System (OBRS)’ to be applied in the sustainable renovation of existing apartment buildings in Taiwan. The developed OBRS consists of five major subsystems: floor subsystem, partition base subsystem, door frame subsystem, sandwich wall panel subsystem and aluminum window frame subsystem. The developed OBRS was further applied in a 90m² 3BR apartment unit to simulate how the system can flexibly respond to three assumed housing renovations during building life cycle. The resulting life cycle costs of three housing renovations adopting the OBRS are compared against those of the conventional renovation system. It’s found that the first cost of OBRS is 31.8% higher than the conventional system; however, the subsequent renovation costs of the OBRS are 30~40% lower than the conventional renovation system. Its accumulated life cycle cost becomes lower in the third renovation (payback time), and its total life cycle cost of three renovations is 11% less than that of the conventional renovation system.

In addition, building information modeling (BIM) technique was explored in the study case to explore the potential benefits or difficulties of BIM applications in building renovation projects. Although may be more time consuming to build a BIM model, it is found that the BIM approach offers an effective way to structure building systems and components to establish appropriate ‘levels’ relationship among systems or components; provides clients with better visualization of interior design schemes during design review meetings, and allows quick estimation of and feedback on renovation costs of alternative design schemes to facilitate and finalize clients’ design decisions.

In conclusion, when applied in the renovation of an existing apartment building, the OBRS is expected to offer (1) spatial flexibility to cope with occupants’ changing needs over time; (2) improved maintainability to facilitate maintenance of pipes and wires; and thus to result in sustainable renovation of existing apartment buildings.
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