

Article

BIM-Based Approach to Simulate Building Adaptive Performance and Life Cycle Costs for an Open Building Design

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Abstract: In the long-term use of buildings, renovations are sometimes required as usage behaviors have changed and residents' demands for space are adjusted. However, the public in general are deficient in renovation knowledge and information regarding building use and its maintenance phases; thus, the initial stage of planning and design often lacks flexibility, leading to waste materials in the subsequent renovation project. Theoretically, Building Information Modeling (BIM) can be used as a building unit resume and renovation benefit prediction tool; moreover, it plays an important role in the usage and maintenance phases. This study develops three design proposals that target different service lives (30 years, 50 years, 100 years), as based on the building's expected life, and uses BIM technology to simulate the life cycle cost and design performance, as based on the renovation scenario analysis of the building's life cycle. The findings show that under the service condition target of 100 years, when the open flexible technique is used for the design, space utilization flexibility is enhanced, pipeline maintenance is convenient, waste is reduced, and performance in life cycle cost is better. BIM can predict performance simply and rapidly according to future usage demand adjustments after the initial design.

Keywords: building information modeling (BIM); building performance; building life cycle cost; open building design; performance simulation

1. Introduction

Collective housing is housing that features spaces and facilities for joint use by all residents, who also maintain their own individual households [1], and is the primary form of metropolitan housing in many Asian regions. In recent years, with economic development and social change, the effective and perpetual use of metropolitan collective housing has become an important topic for housing policy planning [2–4]. When residents are confronted with different living needs in various stages of their life cycle, meaning as the family composition and form change, residential building planning and design should meet the user requirements through sustainable, flexible, and efficient techniques, in order to prolong the service life of residential buildings [5–7].

The open building design means the design and construction of buildings are divided into “support” and “infill” systems. When the support system is completed, the infill component is adopted according to user requirements to build the required indoor structure. This practice can flexibly adjust indoor spaces according to the space demand shifts of a family life cycle, reduce the damage and waste resulted from space adjustment, and lower the renovation and equipment pipeline maintenance costs [8,9]. Conforming to future housing policy and climate, the open building design receives attention from all circles due to its diversity, flexibility, and permanence [10].

While the concept of the open building design has been promoted in Taiwan for more than a decade, market acceptance is universally low, and the number of building cases is obviously small. Improved industrial technology, law development, and living habits require that common cognition of the benefits of the open building design be expanded, in order that builders receive more inducement to implement this design [11,12]. In other words, common people cannot determine whether the higher initial cost of the open building design will bring more benefits and advantages to subsequent building use and maintenance.

With the development of information technology, building information modeling (BIM) applications have been widely explored in academia, architecture, engineering, construction (AEC), and facility management (FM) industries [13,14]. Many studies have indicated that the adoption of BIM can facilitate information integration during the building life cycle and is beneficial to building projects [15,16]. As building use and maintenance phases sometimes exceed 30 years, there can be multiple renovations, repairs, or spatial adjustments, thus the concept of BIM may be an effective tool for subsequent building use and maintenance, as it completely records the information of a building and its components.

This study develops three design proposals that target different service lives (30 years, 50 years, 100 years), based on the expected life cycles of actual cases. The design proposal targeting 30 years adopts the traditional building design, the proposal for 50 years uses the semi-open building design, and the proposal for 100 years adopts the open building design. Based on the renovation scenario analysis of life cycle, this study uses BIM technology to simulate the renovation benefits under different proposals, including evaluating the life cycle costs, evacuation time for residents, ventilation, and illuminance. The study will discuss the advantages of the open building design and the key to prolonging building service life in the future.

2. Application of BIM to Building Industry

2.1. Research Direction of BIM in the Construction Industry

In recent years, BIM has been characterized as a promising tool and approach to address traditional problems inherent in architecture, engineering, and construction (AEC) industries. BIM can be used for several purposes according to various project phases, including visualization, drawings, and cost estimation at the planning stage; forensic analysis and conflict, interference, and collision detection at the design stage; code review and forensic analysis during the permit review process; fabrication or shop drawings and construction sequencing at the construction stage; and facility and maintenance management at the operation stage [13]. BIM has been widely studied by academic and industrial circles. Zhao [17] investigated and analyzed 10 years of documents regarding BIM globally, and reported approximately 10 major research emphases: innovation, mobile computing, return on investment, laser scan, BIM tool, three-dimensional model, intelligence, engineering education, ontology, safety, and 4D CAD integration.

2.2. BIM and the Open Building Design

The open building design categorizes the design and construction of buildings in two levels: “support” and “infill” [18]. The design of community-facing functions should focus on the “support” elements (including long lasting pillars, beams, floor slabs, and vertical pipelines), where the service lives of the components are relatively longer. Conversely, designs for the individual inhabitants should emphasize the “infill” elements (including outer windows, separating walls, floorboards, ceiling, doors and windows, furniture, and horizontal pipelines), where the service lives of the components are shorter. Separating construction planning into these two categories during the design stage establishes a hierarchical concept, which allows the two to be independently acted on. Secondary systems (such as the facade system, rooftop system, stairs/elevators, interior partitioning, kitchen and bathroom, gas, electricity, and drain pipes) can be made and changed individually [10,18–20].

Common open building design technologies can be categorized as follows: raised floor, ceiling, box unit, laying pipes in piping shaft, open conduits and lines, and a drywall partitioning system (as shown in Figure 1). These technologies are capable of being flexible and adjustable to suit a family's needs, which can reduce waste and damage caused by the rearrangement of the spaces, while simultaneously cutting down the cost of renovation and maintenance [21,22]. If the BIM tool is used in the building use and maintenance phase, buildings can be renovated and repaired more efficiently and perpetually.

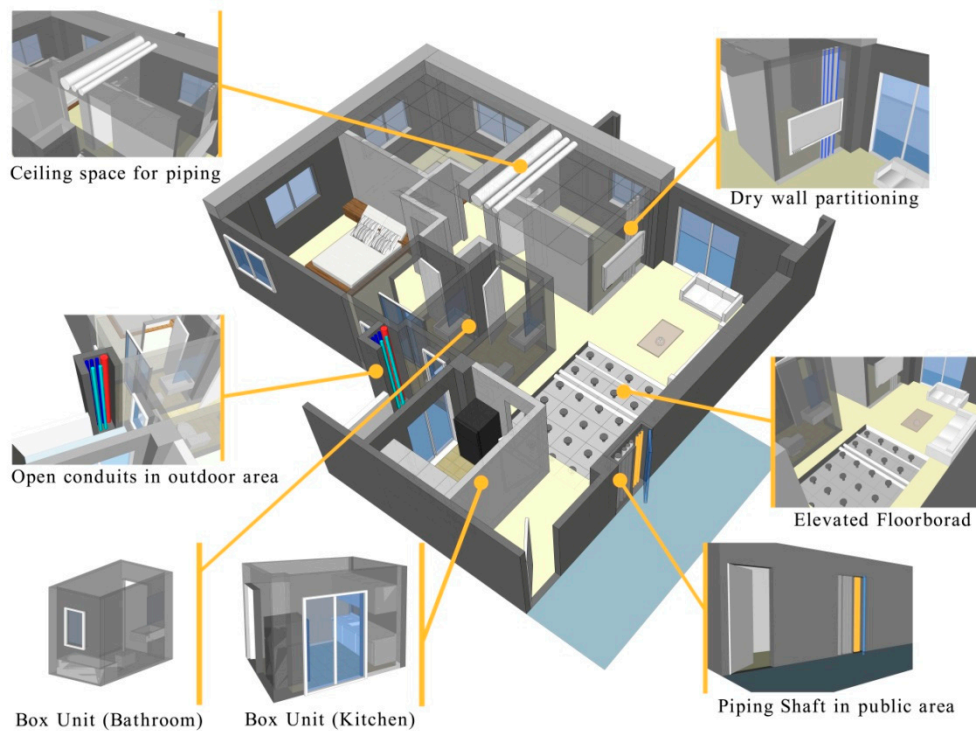


Figure 1. The open building design technologies applied in residential construction.

2.3. Potential of BIM in the Building Use and Maintenance Phase

Buildings and structures differ in types of usage, age, and ownership. Previous studies have revealed that BIM is suitable for larger and more complex buildings, and has been applied by the respondents of recent surveys in commercial, residential, educational, healthcare, and many other building types [23]. It is especially useful in the use and maintenance phase for existing buildings, as the pipeline systems in different buildings are different, and BIM can automatically manage the information of a pipeline system, facilitate routine maintenance of a pipeline system, and conduct first-aid repairs in the case of sudden failure. In the initial stage of building design planning, coordinating BIM with mechanical equipment, the circuit system, and the pipeline system can effectively simulate and integrate building systems, which can reduce subsequent building design and construction costs by 15% to 40%. Moreover, BIM can reduce errors, omissions, and conflicts during future use and maintenance [24,25].

3. Scenario Simulation

3.1. Three Schematic Designs for Different Service Lives

In order to validate the renovation benefits of a life cycle simulated by BIM technology (including a life cycle cost and effectiveness evaluation), this study develops three design proposals that target

different service lives (30 years, 50 years, 100 years) according to the levels of building openness, as described below:

- Proposal A: design proposal targets 30 years, the building is demolished when the 30-year limit expires.
- Proposal B: design proposal targets 50 years, the structure is adjusted for the first time when the 30-year limit expires. The building is demolished after the next 20 years' service (after the 50th year).
- Proposal C: design proposal targets 100 years, the structure is adjusted for the first time when the 30-year limit expires. The structure is adjusted for the second time after another 30 years' service (after the 60th year). The structure is adjusted for the third time when the 90-year limit expires.

In terms of usage scenarios, in all the proposals, building deterioration inspection, improvement, and maintenance (e.g., leakage water handling, wall cracks or paint peeling, choked pipe improvements, equipment overhaul and maintenance) are required after about 15 years' service by the residential building. After 30 years' service, the basic deterioration inspection, improvement, and maintenance are required again, and the indoor structure is adjusted according to user demand (e.g., compartment location and quantity adjustment, changes in spatial location and quantity of bathrooms). The structure adjustment scenario is set as follows: after the first 30 years, due to increased family members and a child's schooling demands, a flexible study unit is added to the original three-room plan. After the second 30 years (60 years), the child obtains employment and leaves home, the structure is adjusted to two rooms. After the third 30 years (90 years), the house is to be sold for commercial use, and used as an office. Taking proposal C as an example, there are at least three relatively large-scale changes in the indoor structure within the 100-year building service life cycle, in order to meet the demands of different generations. The spatial variations are shown in Figure 2.

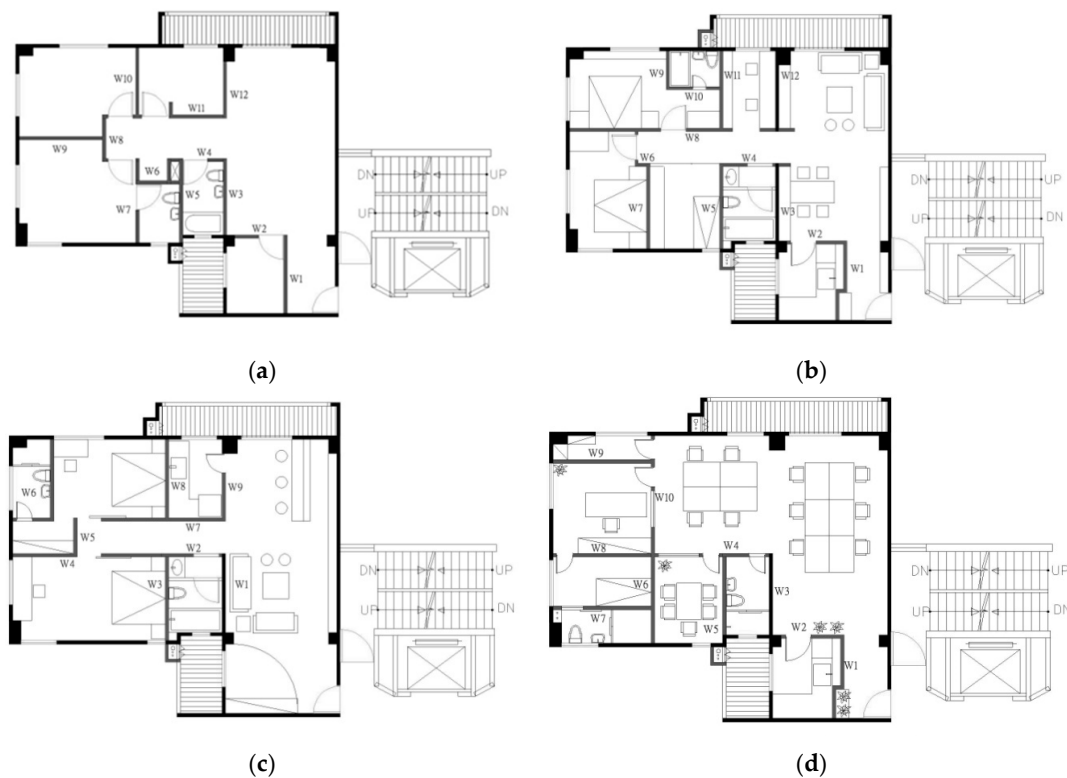


Figure 2. Structure adjustment scenarios. (a) Original structure; (b) the first variation; (c) the second variation; (d) the third variation.

In terms of different schematic designs, the design strategy varies with the goal for service life and building characteristics. In proposal A, the building is demolished when the 30-year limit expires. Therefore, the design features are based on the presently common traditional building designs and construction methods, including ceramic tile floors, frame concealed ceiling, brick partition wall, and concealed pipeline (buried in structure). In proposal B, the structure is adjusted for the first time when the 30-year limit expires, and the building is demolished after the next 20 years' service (after the 50th year). Therefore, the design features are subject to the semi-open building design, where the indoor structure adjustment and the convenience of pipeline maintenance shall be considered. The design and construction methods include a partially open floorboard system, semi-exposed ceiling, descending floor design for water space, light partition wall for compartment, and partially exposed conduits. In proposal C, the structure is adjusted for the first time when the 30-year limit expires. The structure is adjusted for the second time after another 30 years' service (after the 60th year). The structure is adjusted for the third time when the 90-year limit expires. Therefore, the design feature adopts the open building design, where the flexibility of indoor structure adjustment and the convenience of pipeline maintenance shall be considered. The design and construction methods include an open floorboard system, exposed ceiling, descending floor design for water space, light partition wall for compartment, and exposed conduits.

3.2. Introduction to Site

This study uses a site for life cycle design simulation. The simulated design case is a 12-story collective housing unit, where there are four households on each floor (Figure 3). The actual indoor area (excluding balcony and pipe space area) is about 85 m².

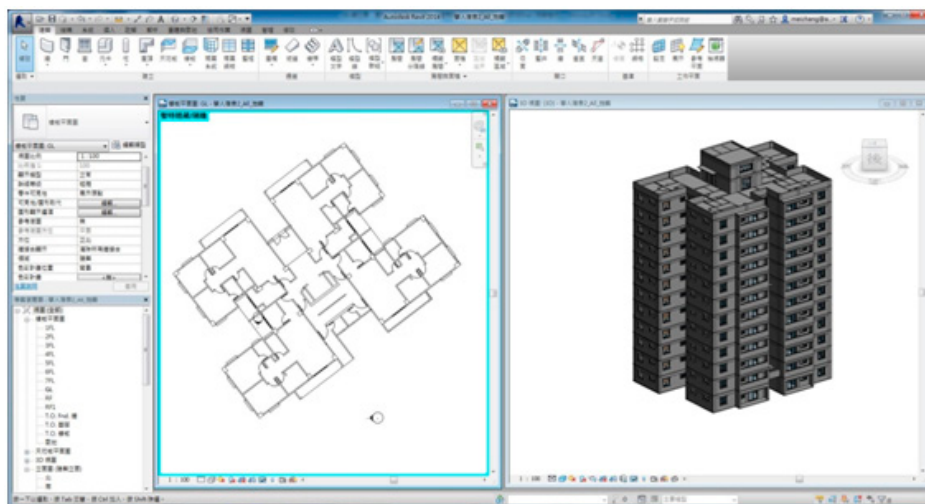


Figure 3. Building Information Modeling (BIM) model of simulation case.

4. BIM Simulation

The BIM model of LOD200 is built according to the current condition of the aforementioned simulation case. The ventilation performance simulation software (Vasari, Stream, Autodesk Beta 3, San Rafael, CA, USA, 2012), daylighting simulation software (Ecotect, Radiance, Autodesk, v.2011, San Rafael, CA, USA, 2011), and evacuation time simulation software (Fire Dynamics Simulator with Evacuation (FDS + EVAC) tool, v.5, VTT, Oulu, Finland, 2007) are used to simulate the performance difference after the indoor structure variation. The purpose of simulation is to validate the simple and rapid performance prediction for future use demand adjustments after the initial design is completed according to the concept of BIM, wherein any future renovation designs can be instantly adjusted.

4.1. Computational Fluid Dynamics (CFD) Simulation of Indoor Wind Field

According to the site condition for case simulation, the weather data used in this study are the yearly data of 2016, and the station is located 300 m away from the site. The predominant wind is northeast all year around, and the annual average wind speed is about 3.0 m/s. For the designs targeting different service lives, there are differences only in the building openness and construction method, but there is little difference in the structures. Therefore, the CFD simulation of a wind field is implemented only for the proposed target of 100 years, as shown in Figure 4.

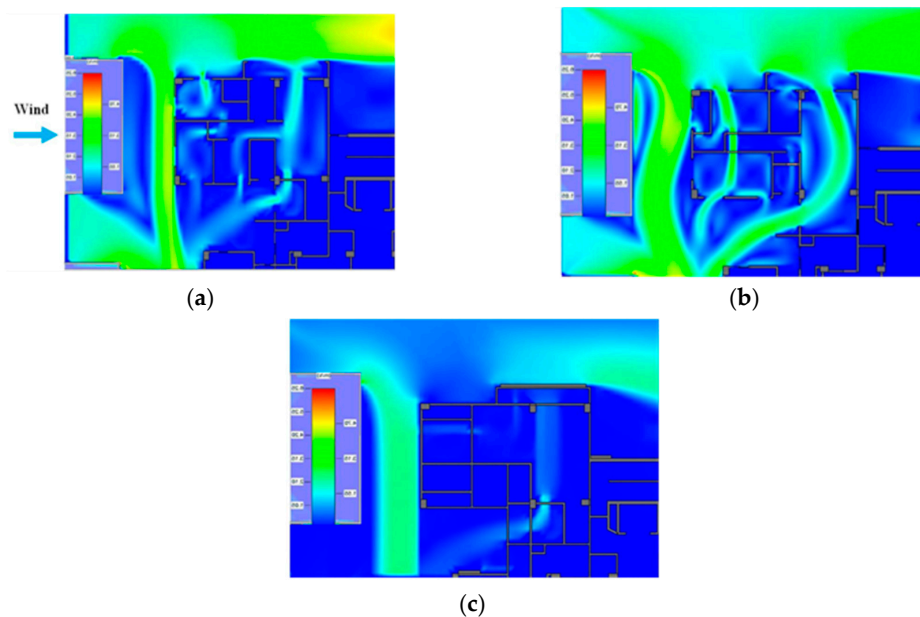


Figure 4. CFD simulation of indoor wind field in the life cycle of the design proposal targeting 100 years. (a) After the first adjustment; (b) after the second adjustment; (c) after the third adjustment.

In the original structure, there is little wind indoors, and the wind speed is about 0.1 m/s. After the first adjustment (30 years), the living room and various rooms have weak and comfortable ventilation, especially in the living room and kitchen, which are connected to the rear balcony, and the wind speed is about 1.5 m/s. After the second adjustment (60 years), as two rooms are changed, when parts of the compartments are demolished, the living room and various rooms have comfortable ventilation, there is a stable air channel in the partial space (e.g., the route from rear balcony to front balcony, opening route of two rooms), and the maximum wind speed is about 3.0 m/s, which is comfortable. After the third adjustment (90 years), as the house is changed into an office, a storage room and a meeting room are created; the local ventilation is influenced, so that only the living room and office area have weak comfortable ventilation, and the overall wind speed is relatively low.

4.2. Indoor Illumination Simulation

The designs targeting different service lives have differences only in the building openness and construction methods; there is little difference in the structure. Therefore, this study uses the daylight analysis software and the proposal targeting 100 years for indoor illumination simulation (based on 9 a.m. of the Summer Solstice). Figure 5 shows the indoor illumination simulation after three structure adjustments.

After the first adjustment (30 years), the living room and various rooms have bright and comfortable illumination, and the living room and kitchen are connected to the rear balcony; however, one sitting room is a dark room. After the second adjustment (60 years), as there are two rooms, when parts of the compartments are knocked down, the rooms have more adequate illumination.

4.4. Life Cycle Cost Analysis

According to the aforementioned renovation scenarios, costs are analyzed according to the unit price and quantity variation information during renovation by BIM (as shown in Figure 7). In the traditional approach to cost estimation, estimators have to digitize the designer's paper drawings or improve their CAD drawings into an estimating package to conduct quantity take-offs. This process may lead to the potential for human errors and propagate any inaccuracies that there may be in the original drawings [26]. Some studies assert that BIM can increase the accuracy in the quantity take-off, especially at the early stage of the design, and allow for a precise future prediction of the construction costs [27]. The BIM model provides the advantage that when a change is made in the design, the change automatically ripples to all related construction documentation and schedules, as well as takeoffs, counts, and measurements that are used by the estimators [28]. In comparison to the traditional approach, the cost estimation of BIM can be done within Revit and output to a Microsoft Excel program that can effectively enhance cost estimation workflows.

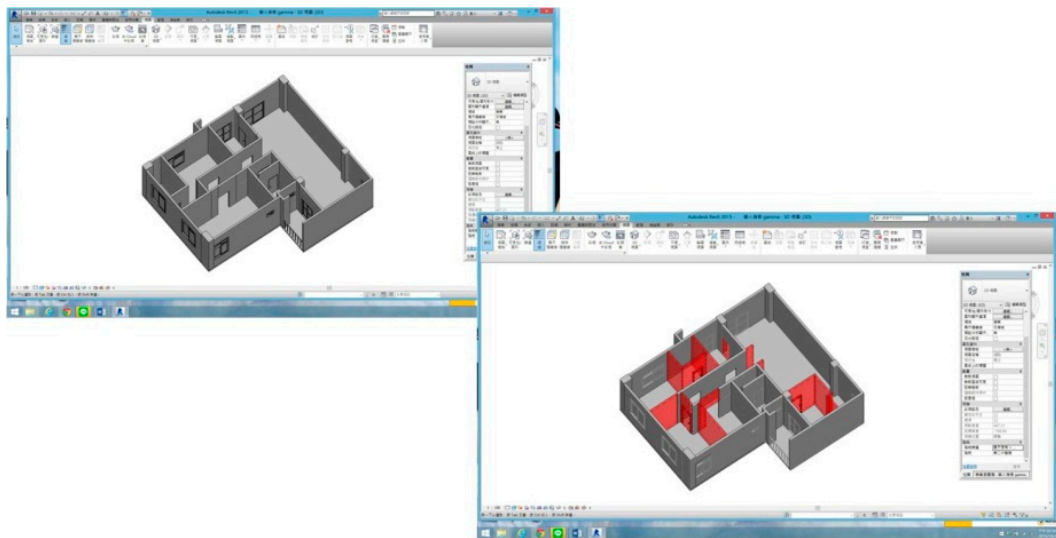


Figure 7. Cost analysis of BIM.

As the three proposals have inconsistent timing of renovation behavior, and as different proposals have different costs of renovation behavior, in order to compare the cost benefits objectively, this study uses Net Present Value (NPV) to analyze the life cycle costs. The lowest minimum acceptable rate of return (MARR) is 3%, and the compared time is the 100-year life cycle. The analysis results are shown in Tables 1 and 2.

$$NPV = \sum_{t=1}^n \frac{C_t}{(1+i)^t} - C_0 \quad (1)$$

where C_t is net cash flow during period t ; C_0 is the total initial investment cost; i is the discount rate; and t is the number of time periods.

Table 1. Renovation behavior analysis in the life cycles of the three proposals.

Time (Year)	Proposal A Traditional Design Renovation Behavior	Proposal B Semi-Open Design Renovation Behavior	Proposal C Open Design Renovation Behavior
0	Initial construction cost	Initial construction cost	Initial construction cost
15	Deterioration improvement	Deterioration improvement	Deterioration improvement
30	Demolish and reconstruct, and change the original structure into a four-room design	Deterioration improvement Adjust structure: change bathroom location, change walls, create study and pipe space	Deterioration improvement Adjust structure for the first time: change bathroom location, change walls, create study and pipe space
45	Deterioration improvement	Deterioration improvement	Deterioration improvement
50	-	Demolish and reconstruct, and change to two-room structure design	-
60	Demolish and reconstruct, and change the original structure into a new two-room structure	-	Deterioration improvement Adjust structure for the second time: change to two rooms, change the locations of bathroom and kitchen, change walls
65	-	Deterioration improvement	-
75	Deterioration improvement	-	Deterioration improvement
80	-	Deterioration improvement Adjust structure: change to office space, change bathroom location, change kitchen location, change and demolish walls	-
90	Demolish and reconstruct, and change the original structure into an office space	-	Deterioration improvement Adjust structure for the third time: change to office space, change bathroom location, change kitchen location, change and demolish walls
95	-	Deterioration improvement	-
100	-	Demolish	Demolish

Note: deterioration improvement involves leakage water handling, wall cracks or paint peeling, choked pipe improvements, equipment overhaul, maintenance, etc.

Table 2. Life cycle cost analysis of the three proposals.

Time (Year)	Proposal A Traditional Design Cost (NT\$)	Proposal B Semi-Open Design Cost (NT\$)	Proposal C Open Design Cost (NT\$)
0	3,500,000	3,850,000	4,200,000
15	353,000	282,000	200,000
30	3,562,400	692,000	440,000
45	353,000	282,000	200,000
50	-	3,650,000	-
60	3,533,800	-	365,000
65	-	282,000	-
75	353,000	-	200,000
80	-	755,000	-
90	3,510,400	-	343,000
95	-	282,000	-
100	-	100,000	100,000
NPV	6,171,000	5,358,000	4,675,000

Note: the values in the table only consider the actual construction costs.

Slaughter [29] indicated that enhancing the elastic design of buildings would be an efficient way to prolong the service life and value of residential buildings, and proposed a relation graph of the designs that accommodate change and building value according to this concept. According to Slaughter’s

theory, while the standardized design may have a low initial cost, the subsequent maintenance, management, and demand shifts will have high cost, and the value may be highly decreased when the building is to be demolished due to discrepant functionality or physical deterioration. On the contrary, while the flexible design has a higher initial cost, the enhancement of the building value is better.

According to the comparison of the life cycle costs of the three schematic designs, the open design of Proposal C has the minimum life cycle cost (NT\$4.675 million). The traditional design of Proposal A has the highest cost (NT\$6.171 million). This result shows that the open flexible building technique for building design not only enhances space utilization flexibility, facilitates pipeline maintenance, and reduces waste, but it also performs better in the life cycle cost evaluation.

5. Discussion

Regarding sustainable development, in comparison to the traditional design engineering of a shorter service life (30 years), a collective housing unit subject to open building design engineering has more economic, environmental, and social benefits. To prolong the service life of buildings and emphasize the permanence of the environment, popularizing open design and techniques (including raised floors, ceiling, box unit, laying pipes in piping shaft, open conduits and lines, and a drywall partitioning system) is an important trend.

In terms of economic benefit, the shock resistance and material durability of the structural system of the open building design targeting 100 years are higher than the designs for 50 years and 30 years, the inhabitants live more safely, the probability of demolishing a damaged structure ahead of time is reduced, and the consumption of reconstruction materials and labor is reduced. While the initial cost of the open system design is higher than the traditional type by about 20%, the life cycle cost of the 100-year operational phase is lower than the traditional system by about 24%. In addition, the open partition walls, raised floors, and exposed conduits can effectively solve handling indoor wall water leakage and structure adjustments, thus greatly reducing temporal and financial consumption.

In terms of environmental benefit, most open design techniques can adopt module designs and dry construction. With the goal of 100 years' service, if the traditional technique is adopted, the waste output will be three times of that of the open technique. In the 100-year service period, as open floorboards, integral bathroom, and open partition wall systems are used, there may be efficient adjustment according to user demands, which increases the flexible layout and variability of the pipeline layout. In addition, the requirements for indoor physical environments (ventilation, daylighting, sound insulation, energy saving, water resistance) of the building design targeting 100 years are higher than that for the designs targeting 50 years and 30 years, meaning that inhabitants will live with greater comfort, energy savings, and health.

In terms of social benefit, the building design targeting 100 years will pay more attention to environmental compatibility and barrier-free environment design, in order that the senility will not affect the inhabitants' living quality in the future, thus greatly enhancing social welfare and commonwealth. Meanwhile, building maintenance accessibility and safety can be enhanced by making specific property management programs, long-term repair maintenance plans, and public safety examination plans.

6. Conclusions

In recent years, due to economic development and social change, the issue of how to use and inhabit metropolitan collective housing effectively has become an urgent topic of housing policy for the government. Prolonging building service life, reducing the probability of demolition, and meeting residents' living needs in the various stages of their life cycle have received continuous attention from the industry.

This study develops three design proposals targeting different service lives (30 years, 50 years, and 100 years) through a simulation case. The design proposal targeting 30 years adopts the traditional building design, the proposal for 50 years adopts the semi-open building design, and the proposal

for 100 years adopts the open building design. The renovation benefits under different proposals can be simulated specifically by a renovation scenario analysis of life cycle and BIM technology, which are the references for the prediction and adjustment of future renovation designs. The findings show that the open flexible technique for building design not only enhances space utilization flexibility, facilitates pipeline maintenance, and reduces the waste yield, but it also has lower life cycle costs than the traditional design by about 24%; thus, the open concept and technique may be popularized continuously in the future.

This study has proved the feasibility of using the BIM tool in the building usage and maintenance phase to simulate future renovation benefits; however, there are still some key suggestions for subsequent study. For example, building a BIM-based decision support system could instantly optimize the renovation costs, benefits, and strategy, which will assist decision-makers to improve the building's service life through appropriate renovation and improvement under reasonable cost and benefit estimations, in order to meet family demands for their future life cycle and living quality.

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