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Developing a Decision Aid for Selecting Low-carbon Refurbishment Solutions for Multi-story Residential Buildings for Subtropical Cities

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ABSTRACT

This paper describes the development of a prototype systematic web-based decision aid for selecting low-carbon refurbishment solutions for multi-story residential buildings in high-density subtropical cities, with special reference to Hong Kong. 88 potential general sustainable refurbishment approaches are identified by a comprehensive literature review, later narrowed down to 39 considered to be relevant to Hong Kong's climatic condition and building characteristics and then to 17 solutions for common areas and 14 for private-occupied areas after interviewing the industry experts and verification by questionnaire survey of occupants. A set of methods is then established through literature review and energy simulation based on a case study, to calculate the CO_2 emission reductions achievable. The system is then described, which includes a set of criteria for identifying *individual* applicable refurbishment solutions, methods of calculating CO_2 emission reductions and parameter input / output and user interface design for a particular building. Finally, a validation process involving industry experts is followed to ascertain the system's practical usefulness and some possible refinements for implementation.

Keywords: Low carbon; Refurbishment; High-rise residential; Subtropical cities; Decision aid

1. Introduction

The building sector is responsible for 40% of energy consumption and 30% of GHG emissions all over the world [1]. Taking into account the massive growth of new construction and the large number of inefficient existing buildings, carbon emissions from the building sector will more than double in the next 15 years if the business-as-usual scenario continues [1]. In developed countries and regions such as UK and Hong Kong, the ratio of new to old buildings is lower than 4% each year [2]. The existence of a huge number of inefficient existing buildings will compound the GHG emissions of a city and efforts to mitigate the carbon intensity of existing buildings are therefore indispensable [3,4]. To explore the options possible, a great number of sustainable refurbishment approaches have been developed for both residential buildings [5,6,7] and non-residential buildings [8,9,10]. The quantification of emission reductions resulting from these approaches remains an area of interest to research scientists [11,12] and provides support for studies of decision making for sustainable refurbishment, e.g. Jaggs & Palmer [13], PRUPIM Developments [14], Kylili *et al.* [15], etc.

Hong Kong has set a goal to mitigate carbon intensity by 50-60% of the 2005 level by 2020 [16] but until now, many of its research projects have been directed at enhancing the energy efficiency of offices and commercial buildings [17]. Exploration of suitable approaches to lower the energy consumption of residential building stocks remains relatively sparse, and mainly focuses on the improvement of insulation [18], glazing systems [19,20] and air-conditioning [21,22]. Some pilot studies have been undertaken of the energy performance of local residential buildings, e.g. in energy audit and analysis [23,24], in energy saving measures [25], and on building energy use models [26].

Hong Kong is a densely populated city, and over 90% of the people live in high-rise apartments, usually of 10-30 stories [24]. The aim of the research, therefore, was to develop a prototype systematic decision aid for selecting low-carbon sustainable refurbishment solutions for multi-story residential buildings in Hong Kong. This involved identifying the sustainable refurbishment solutions available, developing a set of methods for assessing the CO_2 emission reductions of each solution; establishing a systematic system to select the most suitable solutions based on building parameters specified by users; and validating and/or improving it in consultation with industry practice.

2. Literature review

2.1. Overview of sustainable refurbishment

A great number of sustainable techniques have been developed to provide options for the refurbishment of residential buildings [5,27], commercial buildings [8,9] and other types of buildings [28]. Many approaches for lowering operational energy consumption have also been explored, such as by installing wall insulation [18], improving window glazing systems [19,20] and enhancing the performance of air-conditioners [21,22].

With increasing attention on energy performance in the residential sector, some pilot studies have been conducted by researchers e.g. EST [27], CPA [5], Thorpe [6], Burton [29] and Hakkinen *et al*. [11]. These, together with useful findings concerning sustainable refurbishment [2], relevant guidelines [3] and the systems / tools / frameworks for sustainable decision making [14], provide a solid basis for compiling a set of sustainable refurbishment methods. However, these existing sustainable refurbishment approaches have been developed for specific contexts, with EST [27] and CPA [5], for instance, focusing on buildings in West European countries; Burton's [29] work is mainly based on single or multi-family dwellings; and Baker's [8] studies non-residential buildings.

In a typical subtropical city such as Hong Kong, the hot and humid summers result in the significant use of air-conditioners [30]. This, together with the high demand for housing due to intensive population are the two fundamental causes of high and increasing electricity consumption for residential buildings in Hong Kong [18,20,30]. Space cooling is needed for 7 months a year [31] and around 90% of residential units have installed air-conditioners, the average number of installations being about two per unit [23].

High-density living has also become an essential consideration in research in the residential sector and studies have been made on the use of daylight [32], remote sources of lighting [33], potential for applying thermal insulation [18,20], and especially on the simulation of overall building energy performance [23,26]. However, although many other factors influencing the energy end-use in local apartments, such as floor area, number of household members, housing type, and so on [30], have been considered, these are seldom regarded as major characteristics in previous research on the renovation of residential buildings.

2.2. Decision support for sustainable refurbishment

Despite the great number of available sustainable refurbishment solutions on the market, selecting the best refurbishment approach remains difficult, as such selection is a multi-objective optimization problem subject to various constraints and limitations, such as project target, budget, building services type and efficiency, and building envelopes [34]. Although financial benefit is regarded as the primary criteria for sustainable refurbishment, optimal solutions to be considered should include other related factors, e.g. technical factors, carbon emissions, environmental considerations, policy of the government, and social factors. [34,35]. In brief, the aim of decision making in sustainable refurbishment is to maximize the cost-effectiveness of a refurbishment project in relation to energy conservation while maintaining satisfactory service levels and acceptable user comfort, under the particular constraints in operation [34]. Moreover, as the requirements of input data and the reliability of results may vary significantly due to different levels of uncertainty under different assumptions [34], selecting or developing a suitable model whose uncertainty level is consistent with a particular project situation is essential for maximizing its chance of success. To this end, Ma *et al*. [34] provide an introduction to the key steps in decisions for sustainable refurbishment projects, with performance according to various solutions being analyzed quantitatively using various approaches such as by employing energy models, economic analysis tools and risk assessment methods [34].

Sustainable refurbishment assessment is a vitally important aspect of this and has been intensively studied throughout the process of refurbishment projects. Examples include studies of building energy audits and surveys [13,28], building performance assessment and diagnostics [36], quantification of building energy conservation [12,37], as well as economic analyses [38], risk assessment [39] and the measurement and verification of energy savings [40].

Generally, it is usual to treat embodied energy and ongoing energy consumption separately, where the embodied emissions of materials include the GHGs emitted in manufacturing, transportation, construction process, and demolition [41]. Previous research has shown that the amount of direct GHG emission is proportional to the amount of energy consumption [42] involved in these processes. There is, however, no direct relationship between the amounts of embodied carbon and embodied energy due to GHG emitted in the inherent process of forming materials [43]. Chen *et al*. [41], for instance, adopt multiple data sources of energy consumption in the manufacturing phase, and analyze the energy consumed in transportation by determining the proportion of materials imported from different countries and their corresponding distances from Hong Kong, Two carbon audit toolkits have also been developed to assess embodied GHG emissions for small and medium enterprises [44] and households [45] in Hong Kong.

As the quantification of energy savings plays an essential role in decision making for sustainable building refurbishment [34], considerable research has been conducted in this area. Ongoing energy savings from building refurbishment are frequently assessed by simulation tools, such as in the application of insulation layers [31,35], upgrading window glazing [18,19,20], and improvements in sealing against air leakages [46]. Rysanek & Choudhary [47] establish a new building physics and energy supply system simulation engine for analyzing the effects of various carbon-reducing retrofit options, while Yalcintas [48] estimates the difference in energy consumption between pre-retrofit and post-retrofit scenarios based on Artificial Neural Networks (ANN).

In addition to such simulation methods, electricity consumption can be directly calculated for some building service devices, such as highly efficient fluorescent lighting [49], LED lighting [50], and photovoltaic panels [51]. Murray *et al*. [12] uses case study research to assess the emission reductions of refurbishment using two different modeling approaches and proposes a modeling technique that is sufficient to support decision making; Asadi *et al*. [37] develops a multi-objective mathematical model to optimize the energy benefits of building retrofits, in which all available combinations of alternative refurbishment solutions can be considered simultaneously; and Raftery *et al*. [52] describes an evidence-based methodology for calibrating whole building energy models, which can be used to estimate the energy savings of different refurbishment approaches.

While numerous studies have been undertaken to explore the *life cycle* carbon emission and energy consumption of commercial buildings [43,53], little literature focuses on the residential sector. Exceptions are studies of the life cycle energy consumption of single dwellings in Sweden [54] and on the embodied energy in building materials in the whole life of high-rise residential blocks in Hong Kong [53]. However, although the importance of building life cycle emissions has been widely recognized [46], they are not frequently considered in the study of sustainable refurbishment due to difficulties in collecting reliable operational data [51]. An exception in Hong Kong is Cole & Wong [55] (cited in [41]), who investigated the life cycle energy consumption of a high-rise residential building including consumption of embodied energy, operational energy and energy consumed in demolition.

3. Methodology

3.1. Identification of sustainable refurbishment solutions

88 existing sustainable refurbishment solutions were identified from the literature, and a desktop study was conducted to identify the solutions most relevant to the local situation. A series of semi-structured interviews was then conducted with experienced industry experts representing different stakeholder groups such as government, consultants, private developers, and academics holding senior positions in their organizations to learn the applicability of the proposed refurbishment solutions. The responses from the interviews were coded,

categorized, and summarized as to whether and why a solution was applicable, and what were the principles for selecting a solution.

Street intercept surveys were also conducted in order to (1) learn occupants' acceptance or rejection of the proposed refurbishment options; and (2) explore the relationship between occupants' basic information and the acceptance level of the solutions. The survey data was analyzed in terms of basic information, (including age, residence type, and education level) and the acceptance level of each refurbishment solution. Pearson Chi-Square Tests at the 10% level of all the groups under the basic information variable failed to detect any significant heterogeneity of responses.

Finally, of the 88 sustainable refurbishment approaches identified, 49 were considered irrelevant to the Hong Kong climatic condition and building characteristics; another 8 methods were eliminated after interviewing the industry experts, and the occupants' acceptance of the solutions for private-occupied areas was confirmed from the questionnaire survey. This resulted in the identification of 17 sustainable refurbishment solutions for common areas and 14 solutions for private-occupied areas.

3.2. Assessment of emission reductions

A case study was carried out to determine the potential emission reduction performance of various refurbishment approaches. A typical residential housing was first selected as a standard model and the methods for emission assessment of each sustainable refurbishment solution were developed by identifying the system boundary and calculation methods to determine the potential emission reductions for refurbishing the target building.

The target building was chosen to reflect the common features of Hong Kong's existing buildings as much as possible and being old enough to have potential for sustainable refurbishment. Previous studies of sustainable refurbishment were reviewed in order to establish the boundary of carbon emission. For instance, for refurbishment approaches such as replacing building service equipment and changing user habits, only operational emissions were considered in the assessment while, for replacing window glazing, installing shadings, and photovoltaic panels, both embodied *and* operational emissions were taken into account.

After reviewing the features of major building energy simulation tools developed in recent years [56], eQUEST was selected for analyzing the energy performance of the building. This performs an hourly simulation of various energy-consuming devices, including chillers, boilers, pumps, lighting, fans and other appliances, and allows multiple simulations to compare alternative outcomes. In the *operational stage*, the refurbishment initiatives were divided into two groups using different methods of analysis. For installing, adjusting and replacing building service devices like lighting, pumps and lifts, the energy conservation was directly calculated based on the corresponding parameters and formulae proposed in the literature. For the approaches with significant impacts on the building's thermal load (such as replacing windows, improving insulation and air sealing, installing overhangs and vertical fins, alterations of building envelopes and some behavior changes like resetting air conditioner temperature), energy simulation was preferred to assess baseline consumption and subsequent conservation. When the energy savings were determined, their carbon emission reductions were calculated using the emission factors provided by the corresponding power company. The amount of *embodied carbons* was calculated by multiplying the mass of materials identified according to the requirement of building codes or site measurement by corresponding emission factors. Finally, the overall emission reduction of each refurbishment solution was determined from the difference between operational emission reduction and embodied carbon.

3.3. System development process

Fig. 1 illustrates the process of developing the system. The system architecture was first designed to illustrate the components involved, the relationships among the components and the decision flow of the program. After learning the needs and features of target users, the input / output variables and formulae for emission assessment were specified based on the developed assessment methods. Then, the form and development software were selected according to the features of decision flow and the needs of users. Using the proposed software, the system was developed through programming and then released to users after debugging.

< Figure 1 >

3.4. Validation

A case study was used to determine the potential emission reductions of refurbishing a residential building as a check on the various assumptions made in the system's emission assessment, effectiveness of the calculation methods used and ease of operation. This involved a further series of interviews similar to those already described with the addition of an initial 15-minute presentation introducing the sustainable refurbishment solutions and emission calculation methods, and to demonstrate the system. The interviewees were then invited to validate the research findings by completing a questionnaire. Finally, further comment was solicited on the ways to improve the refurbishment outcomes.

4. Development of the system

4.1. System architecture

Fig. 2 presents the architecture of the system. This includes four components, namely: input, operation program, database and output. The operation program is designed for assessing the suitability of refurbishment options and calculating their emission reductions according to the input parameters. The database contains a list of sustainable refurbishment solutions, their scope of application and formulae for calculating the emission reductions of each solution. The decision flow is as follows:

a) *Input*: users are asked to specify the characteristics of their building, including the parameters of envelope, building service, annual energy consumption and occupant features;
b) *Applicability assessment*: the applicability of each solution is assessed by checking whether the relevant input building parameters satisfy the specified criteria of the solution;
c) *Emission calculation*: using the embedded calculation methods, the emission reductions of the applicable refurbishment solution are determined according to the input parameters;
d) *Output*: a list of sustainable refurbishment solutions is produced with quantitative values of emission reductions.

< *Figure 2* >

4.2. Emission assessment methods and input / output variables

Numerical input variables

From the case study, a set of formulae for calculating the emission reductions of each sustainable refurbishment solution was developed (Tables 1 and 3). These formulae are integrated into the system and their variables identified as numerical inputs (Table 4). These variables consist mostly of the power and number of building services and appliances in use, while others include daily / reduced operation hours, thermostats for water heating and air cooling, number of occupants, and annual consumption of electricity, gas and water. The energy savings and emission reductions of the identified sustainable refurbishment solutions are calculated according to these input variables using the specified formulae.

< Table 1 >

< Table 2 >

< Table 3 >

< Table 4 >

Non-numerical input variables and logical arrangements

Based on the characteristics of the sustainable refurbishment solutions, two lists of non-numerical variables are derived to identify the opportunities for applying these solutions to common areas (Table 5) and privately-occupied areas (Table 6). The alternatives for each item are introduced with logical rules for enabling / disabling the use of corresponding solutions. Most of the variables are used to specify the type of building service / appliance / windows in use, which can determine the selection of the formula for calculation and eliminate the approaches that are not applicable or already exist in the building. Those of items such as time switches and daylight sensors can be enabled / disabled according to a simple judgment by the user, e.g. by checking whether there is sufficient daylight in the corridors. In this way the applicability of the solutions is determined according to the current situation.

< ***Table 5*** >

< ***Table 6*** >

Outputs

The system has five outputs: suitable sustainable refurbishment solutions are presented after checking for applicability for the various inputs; the quantitative values of energy saving and emission reduction for each solution are calculated and shown using the specified formulae and numerical inputs; and the percentages of total consumption and emissions.

Development software

The target users are the owners and occupants of high-rise residential buildings, which include most of the general public. In order to promote its use, it is highly preferable to provide these people with easy means of access. In addition, stability of operation and a high response speed needs to be ensured to provide better user experience. Based on these considerations, a web application was selected as an appropriate environment. The application is based on a software service model and allows users to accomplish tasks on a web site [71]. This exploits Baxley [72] and Turnbull's [73] three advantages of using web applications – ease of access, ease of deployment and the presence of a mature database. It will also help developers to update and improve the system over time and enable the user input data to be saved as examples of possible refurbishment cases for future research into sustainable refurbishment. Apache Tomcat™, JavaSever Pages™ (JSP), and MySQL™ were used due to their ready availability and low cost.

4.3. Programming

Framework of the web application

A combination of Tomcat and MySQL provides a powerful and reliable platform for developing and deploying JSP applications [74] and Fig. 3 presents the framework for the web application. The major steps of this are [74,75,76,77]:

(1) A request is sent from the client's web browser to the web server using Hyper Text Transfer Protocol (HTTP) format;

(2) The web server recognizes the HTTP request and sends it to a JSP engine;

(3) The JSP engine loads the JSP file, converts it into a Java servlet, which is sent to the servlet engine;

(4) The servlet engine executes the Java servlet according to the request and produces an output to the web server in HTML (Hyper Text Markup Language) format. During the execution of the servlet, CRUD (create, read, update and delete) operations are implemented to the database in MySQL.

(5) The web server forwards the HTTP response to the client's browser.

< *Figure 3* >

Process of programming

In the development process of the web application, a database was first built to define the attributes of different types of data, e.g. the power used by, and number of units of, each appliance. Then the calculation methods and the logical rules for enabling / disabling the applications of the sustainable refurbishment solutions were coded using Java language. A system interface was designed to provide the input and output and the CRUD (create, read, update, and delete) operations were also programmed at this stage. Finally, after several debugging sessions, the prototype system was released to a limited number of users for validation purposes.

4.4. System operation flow

The web application automatically selects suitable sustainable refurbishment solutions and calculates the emission reduction of these solutions based on the building parameters input by the user. The system interface and procedure for its operation involves three basic steps shown in Fig. 4.

< ***Figure 4*** >

Step 1: Create the case for sustainable refurbishment according to a specified type

Fig. 5 shows the main menu for the decision process. To create a new case, users need to specify the type of refurbishment by clicking “Add Private Case” or “Add Public Case”. Users can also perform CRUD operations for editing the cases through this menu.

< ***Figure 5*** >

Step 2: Input the building parameters

Fig. 6 shows the first part of the input interface, which is for collecting basic project information. This information is not involved in the emission assessment. The second part of input is presented in Fig. 7, which contains the numerical and non-numerical items identified earlier.

< ***Figure 6*** >

< ***Figure 7*** >

Step 3: Display the results

Fig. 8 shows the output results of the system. The upper table provides a list of sustainable refurbishment solutions ranked in ascending order of refurbishment levels together with the energy saving and CO_2 emission reduction values for each solution. In the lower table, the sum of total energy and emission performance for each refurbishment level are determined and exemplified.

< ***Figure 8*** >

4.5. Validation

Of 40 contacted potential interviewees, 6 – comprising 3 government officials, 1 consultant and 2 academics - participated in the interviews. Table 7 shows their profile.

< ***Table 7*** >

After the short presentation the interviewees spent 10 minutes validating the sustainable refurbishment solutions (Table 8), the methods of assessing emission reductions (Tables 1 and 4) and the program interface. Each interviewee rated the system in terms of its *comprehensiveness* (how comprehensive are the proposed refurbishment solutions, *implementability* (whether the proposed solutions can be implemented in real projects), *accuracy* (how accurate are the estimated emission reductions); *effectiveness* (whether the system can make improvements in sustainable refurbishment) and *user friendliness* (understandability of the interface and ease of operation). Table 9 shows the results, with scores on a five-point scale from 1 (“fail”) to 5 (“excellent”).

< *Table 8* >

< *Table 9* >

Comments

Further comments from the interviewees highlighted several important ways to improve the system. In summary, these are that a detailed introduction and explanation needs be given for each item displayed in the input / output interface to help users understand the meaning of the variables involved. This can ensure the improved implementability of the refurbishment solutions and enhance the user-friendliness of the interface. Secondly, rather than merely dividing a building into privately-occupied area and common areas, more scenarios should be considered, such as different building types (i.e. public or private), ages and sizes. The more specifically the scenario is defined, the higher level of accuracy and implementability can be achieved with the system. Thirdly, experiments or in-depth analyses are recommended to further examine the accuracy of the developed emission calculation methods. Finally, more information could be presented in the results, e.g. by using graphs to show the energy benefits, providing reference cases, and producing a report of solutions, to enhance user-friendliness.

5. Conclusions

Despite the fact that much experience of sustainable refurbishment has been accumulated in other regions, the climatic condition and building characteristics of high-density subtropical cities such as Hong Kong renders a portion of this inapplicable to the local situation. This paper helps to address this problem by developing a list of suitable sustainable refurbishment solutions for multi-story residential buildings in Hong Kong. The developed solutions form a solid basis for future research into sustainable refurbishment, with consideration of various aspects such as cost, human behavior, policy and decision support. A particular contribution is the system boundary method and calculation methods used to overcome the difficulties involved in determining the CO_2 produced for each sustainable refurbishment solution over the building life cycle.

A major practical advantage of the system is the simple building parameter input required of lay users. As emission reductions are considered to be one of the most important factors in sustainable refurbishment, the developed system can play an essential role in selecting the best sustainable refurbishment solutions for residential buildings in Hong Kong and provides the basis for the development of similar such aids in other high-density subtropical cities, thus helping promote the development of sustainable refurbishment and the achievement of associated CO_2 emission reductions in general.

A limitation of the empirical results of the work is that they are restricted to high-rise residential buildings based on a case study of a typical Hong Kong public housing scheme. However, the *method* used in developing the system is has no such restrictions and should be capable of being followed for any form of construction work anywhere. The potential for future research is to extend the current sole focus on energy and carbon emissions savings to other factors such as cost, human intervention, environment, and culture. Similarly, the current restriction to operational and the total embodied carbons can be extended to other phases of a building's life cycle, such as construction and demolition, although these are generally considered to make a relatively small contribution. Finally, although the system has been validated by industry experts, which is effective for evaluating the refurbishment solutions and system interface, experiments or in-depth data analyses will provide a better validation of this part of the overall research outcome.

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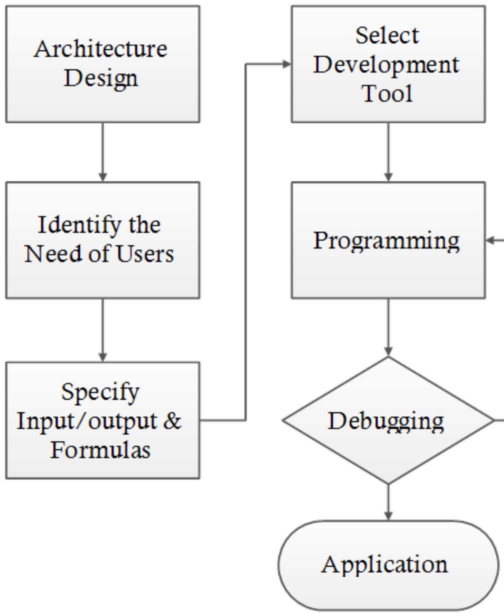


Figure 1: System development process

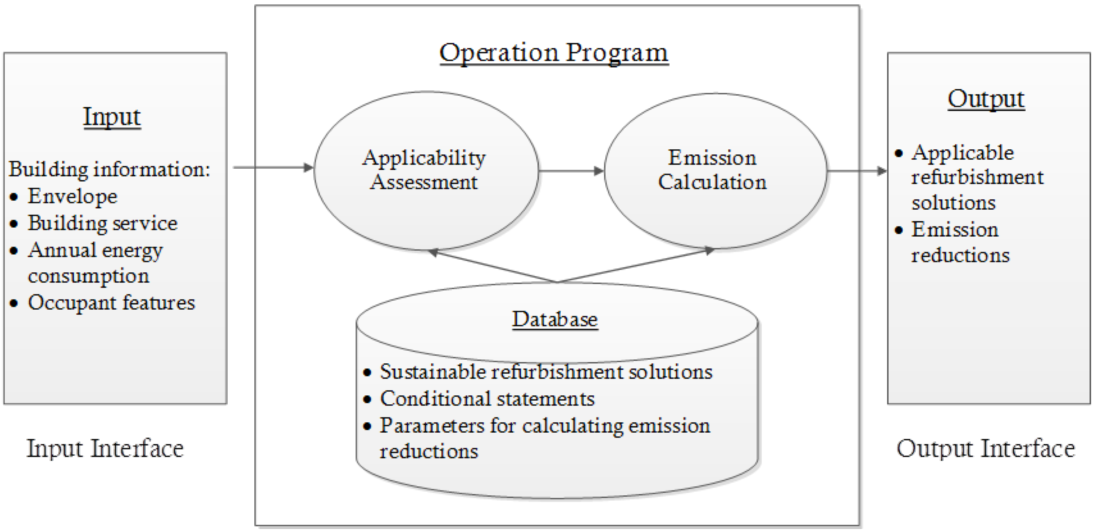


Figure 2: System architecture

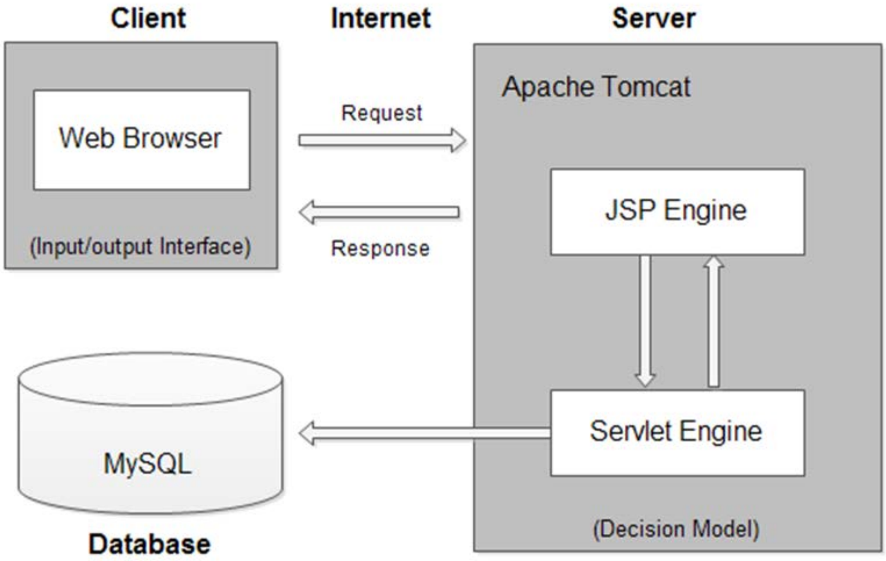


Figure 3: Framework of the web application

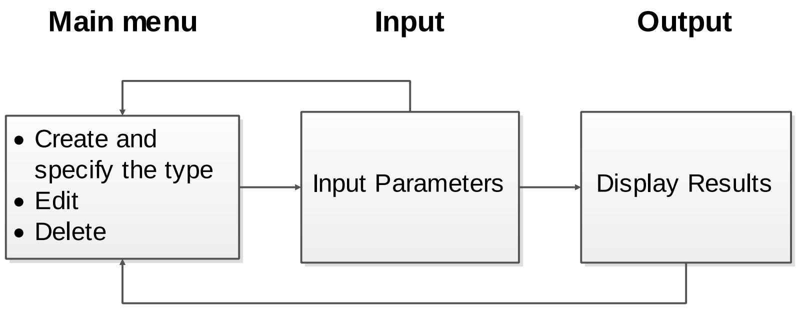


Figure 4: Operation flow

Figure 5: Main menu

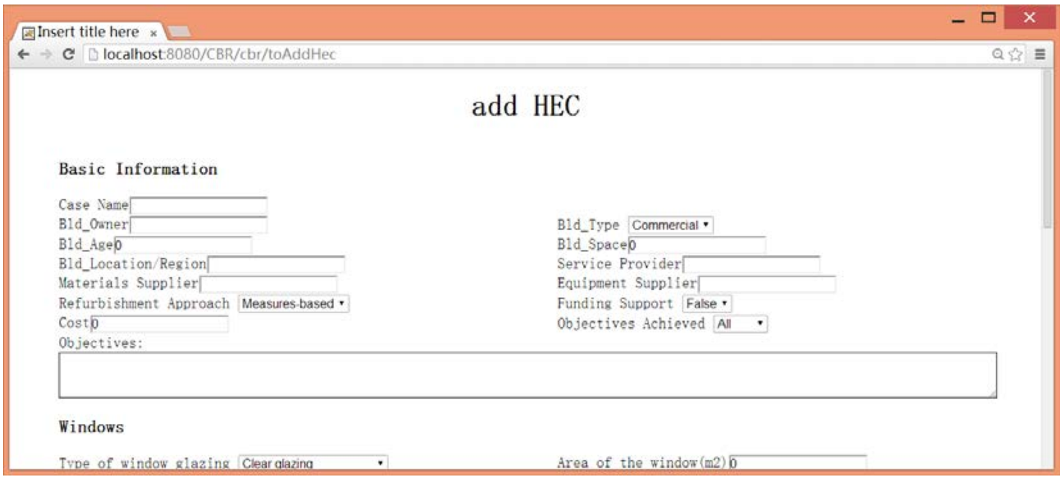


Figure 6: Input of basic project information

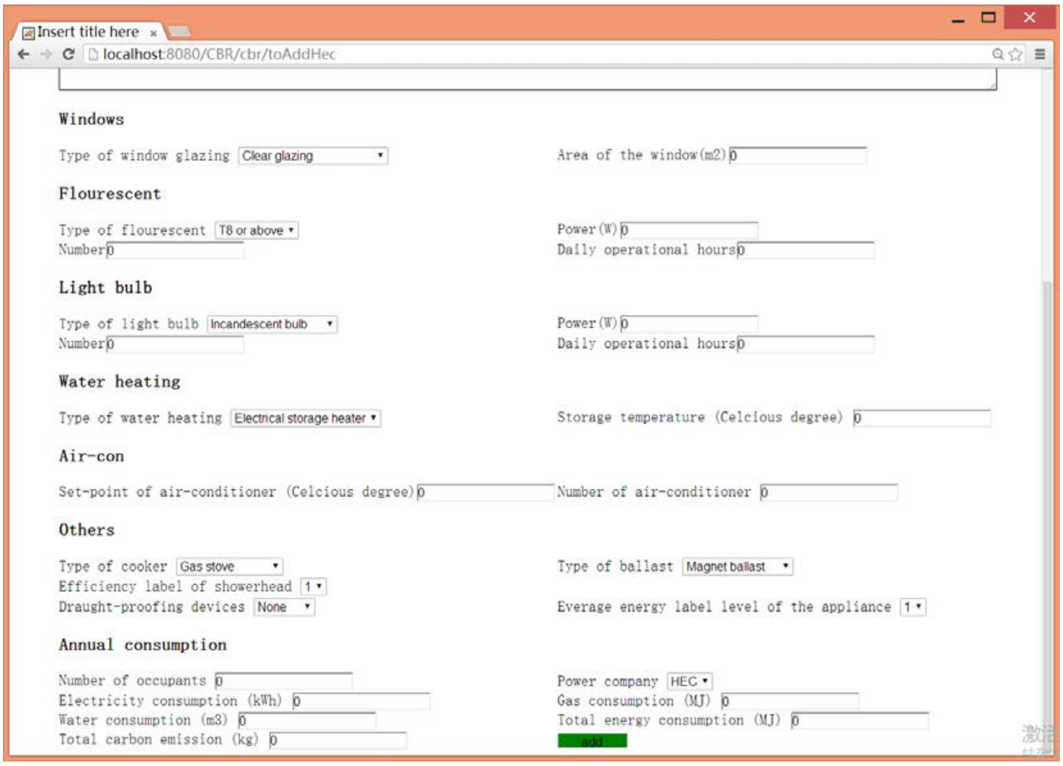
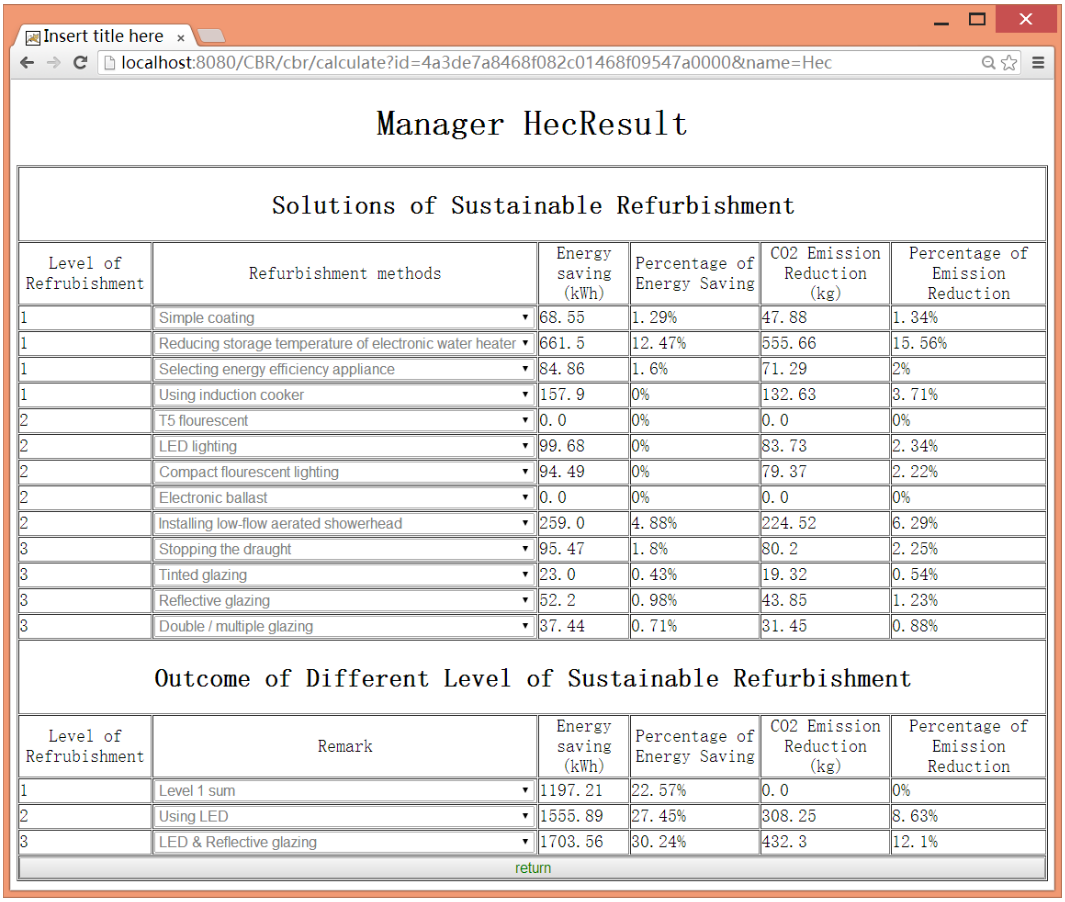


Figure 7: Numerical and non-numerical inputs



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localhost:8080/CBR/cbr/calculate?id=4a3de7a8468f082c01468f09547a0000&name=Hec

Manager HecResult

Solutions of Sustainable Refurbishment

Level of Refurbishment	Refurbishment methods	Energy saving (kWh)	Percentage of Energy Saving	CO2 Emission Reduction (kg)	Percentage of Emission Reduction
1	Simple coating	68. 55	1. 29%	47. 88	1. 34%
1	Reducing storage temperature of electronic water heater	661. 5	12. 47%	555. 66	15. 56%
1	Selecting energy efficiency appliance	84. 86	1. 6%	71. 29	2%
1	Using induction cooker	157. 9	0%	132. 63	3. 71%
2	T5 flourescent	0. 0	0%	0. 0	0%
2	LED lighting	99. 68	0%	83. 73	2. 34%
2	Compact flourescent lighting	94. 49	0%	79. 37	2. 22%
2	Electronic ballast	0. 0	0%	0. 0	0%
2	Installing low-flow aerated showerhead	259. 0	4. 88%	224. 52	6. 29%
3	Stopping the draught	95. 47	1. 8%	80. 2	2. 25%
3	Tinted glazing	23. 0	0. 43%	19. 32	0. 54%
3	Reflective glazing	52. 2	0. 98%	43. 85	1. 23%
3	Double / multiple glazing	37. 44	0. 71%	31. 45	0. 88%

Outcome of Different Level of Sustainable Refurbishment

Level of Refurbishment	Remark	Energy saving (kWh)	Percentage of Energy Saving	CO2 Emission Reduction (kg)	Percentage of Emission Reduction
1	Level 1 sum	1197. 21	22. 57%	0. 0	0%
2	Using LED	1555. 89	27. 45%	308. 25	8. 63%
3	LED & Reflective glazing	1703. 56	30. 24%	432. 3	12. 1%

return

Figure 8: Results display

Table 1: Methods of calculating the energy savings of the sustainable refurbishment solutions

Refurbishment solutions	***Formula of calculating annual energy saving***	***Reference***
T5 fluorescent	$\mathrm{E} = \sum P \times N \times H \times 0.33 \div 1000$ where E = annual energy saving (kWh); P = power of the original fluorescent (W); N = number of fluorescent; and H = annual operation hours	[49]
LED lighting	$\mathrm{E} = \sum P \times N \times H \times 0.77 \div 1000$ where E = annual energy saving (kWh); P = power of the original lighting (W); N = number of lightings; H = annual operation hours	[50]
Compacted fluorescent lightings	$\mathrm{E} = \sum P \times N \times H \times 0.75 \div 1000$ where E = annual energy saving (kWh); P = power of incandescent lamp (W); N = number of lightings; H = annual operation hours	[57]
Electronic ballast	$\mathrm{E} = \sum P \times N \times H \times 0.25 \div 1000$ where E = annual energy saving (kWh); P = power of fluorescent (W); N = number of lightings; H = annual operation hours	[58]
Daylight sensors	$\mathrm{E} = \sum P \times N \times H \div 1000$ where E = annual energy saving (kWh); P = power of lightings (W); N = number of lightings under control; H = reduced annual operation hours	N.A. (Direct calculation)
Motion sensors	$\mathrm{E} = \sum P \times N \times 24 \times 365 \times 0.3 \div 1000$ $= \sum P \times N \times 2.628$ where E = annual energy saving (kWh); P = power of lightings (W); N = number of lightings under control	[59]

Lift with power regeneration system	$E = \sum E_0 \times P \times 0.2$ where E = annual energy saving (kWh); E_0 = original annual energy consumption of lifts (kWh); the method of calculating E_0 is shown in Table 2.	[59]
Lifts with advanced VVV-F control system	$E = \sum E_0 \times P \times 0.4$ where E = annual energy saving (kWh); E_0 = original annual energy consumption of lifts (kWh); the method of calculating E_0 is shown in Table 2.	[60]
Permanent magnet synchronous lift motor	$E = \sum E_0 \times P \times 0.2$ where E = annual energy saving (kWh); E_0 = the original annual energy consumption of lifts (kWh); the method of calculating E_0 is shown in Table 2.	[59]
Green roof	$E = E_{total} \times 0.1$ where E = annual energy saving (kWh); E_{total} = overall energy consumption (kWh); the savings are only available to the residents in the top three stories	[61]
Rearrangement of lighting circuits to fully utilize daylight corridors	$E = \sum P \times N \times H \div 1000$ where E = annual energy saving (kWh); P = power of lightings (W); N = number of lightings reduced; H = reduced annual operation hours	N.A. (Direct calculation)
Photovoltaic panels	$E = A \times 120 \times 0.8 \div \cos 22° = A \times 104.3$ where E = annual energy generation (kWh); A = roof area (m^2)	[62]
Time switches	$E = \sum P \times N \times H \div 1000$ where E = annual energy saving (kWh); P = power of lightings (W); N = number of lightings under control; H = reduced annual operation hours	N.A. (Direct calculation)
Replace water pumps with higher efficiency one	$E = \sum P \times N \times H \times 0.02$ where E = annual energy saving (kWh); P = power of pumps (kW); N = number of pumps; H = annual operation hours	[63]
Simple coating	$E = E_{total} \times 0.2 \times 0.05$	[64]

	where E = annual energy saving (kWh); E_{total} = overall energy consumption (kWh)	
Stopping draughts	$E = E_{total} \times 0.018$ where E = annual energy saving (kWh); E_{total} = overall energy consumption (kWh)	[65]
Installing low-flow aerated showerhead	$E = E_{total} \times 0.5 \times 0.17$ where E = annual energy saving (kWh); E_{total} = overall energy consumption (kWh)	[66]
Reducing storage temperature of electric water heater	$E = N_o \times 55.2 \times \Delta T \times 4.2 \times 10^3 \times D \div (3.6 \times 10^6)$ $= \Delta T \times N_o \times D \times 0.0644$ where E = annual energy saving (kWh); N_o = number of occupants; ΔT = reduced temperature (℃); D = number of days using hot water	[67]
Selecting energy efficiency appliance	$E = E_{total} \times (0.2 \times 0.15 + 0.16 \times 0.25) = E_{total} \times 0.07$ where E = annual energy saving (kWh); E_{total} = overall energy consumption (kWh)	[68]
Using induction cooker	$E = E_{total} \times 0.257 \times 0.3 = E_{total} \times 0.077$ where E = annual energy saving (kWh); E_{total} = overall energy consumption (kWh)	[69]

Table 2: Method of calculating the annual consumption of lifts

Type	***Number of lifts***		***Annual energy consumption (kWh)***
	N<3	***N>=3***	
AC variable voltage control	K1=1.6, K2=0.5	K1=1.6, K2=0.3	$E_0 = K1 \times K2 \times 0.35 \times H \times 200000 \times P \div (3600 \times 2)$ where E_0= annual energy consumption (kWh); H = total travel of lifts (m)
Variable voltage variable frequency	K1=1.0, K2=0.5	K1=1.0, K2=0.3	
Power regeneration system	K1=0.6, K2=0.5	K1=0.6, K2=0.3	
Permanent magnet synchronous motor	N.A.	N.A.	

Source: Nipkow & Schalcher, 2006 [70]

Table 3: Overall emission reductions per flat of the refurbishment solutions in private-occupied area

Refurbishment solutions	**Operational energy savings (kWh)**	**Operational emission reduction (kg CO_2)**	**Embodied carbon emission (kg CO_2)**	**Annual emission reduction (kg CO_2)**	**Percentage of total emission (%)**
Simple coating	48	38	n.a.	38	1.20
Tinted glazing	22	17	0.004	17	0.53
Reflective glazing	44	34	0.004	34	1.07
Double / multiple glazing	31	25	0.012	25	0.79
Stopping the draught	86	68	n.a.	68	2.14
Installing low-flow aerated showerhead	408	322	n.a.	322	10.13
Reducing storage temperature of electric water heater	336	266	n.a.	266	8.37
Reconfiguring air conditioner's temperature	187	148	n.a.	148	4.66
Selecting energy efficiency appliance	336	265	n.a.	265	8.34
Using induction cooker	397	313	n.a.	313	9.85
Total	*1895*	*1496*	*0.02*	*1496*	*47.07*

Table 4: Numerical inputs for emission estimation

Common area		***Private-occupied area***
Lighting	Daylight sensors	Fluorescent
Power (W)	Power (W)	*Power (W)*
Number	Number	*Number*
Daily operation hours	Reduced operation hours	*Daily operational hours*
Lifts	Motion sensors	Light bulb
Power (kW)	*Power (W)*	*Power (W)*
Height of building (m)	*Number*	*Number*
Number	*Reduced operation hours*	*Daily operational hours*
Pumps	Roof area (m^2)	Hot water storage temperature (°C)
Power (kW)	Annual energy consumption	Set-point of air-conditioner (°C)
Number	*Public zone (kWh)*	Number of occupants
Time switch	*Private zone (kWh)*	Annual consumption
Power (W)		*Electricity (kWh)*
Number		*Gas (KJ)*
Reduced operation hours		*Water (m^3)*

Table 5: Non-numerical inputs for refurbishment in common areas

Item	***Options (fixtures that are already in place)***	***Rules for selecting solutions***
Type of lighting	A. T8 or T12 fluorescent B. T5 fluorescent C. Incandescent lighting D. Compacted fluorescent lighting (CFL) E. LED lighting	Add a type of lighting. If A is selected, replacement with T5 is applicable. If C is selected, replacement with CFL and LED is applicable
Type of ballast	A. Magnet ballast B. Electronic ballast	If A is selected, replacement with electronic ballast is applicable
Current lift system	A. Conventional standard control B. Variable voltage variable frequency (VVVF) system C. Power regeneration system D. Permanent magnet synchronous lift motor	If A is selected, replacement with the other three systems is applicable. If B, C, or D is selected, the corresponding approach is disabled
Current pump system	A. Conventional speed pumps B. High efficiency pumps C. None	If A is selected, replacement with high efficiency pumps is applicable
Time switch Daylight sensor Motion sensor Green roof Overhangs Vertical fins Rearranging light circuit Photovoltaic panels	A. Enabled B. Disabled	Enable or disable the use of the item
Power company	A. Hongkong Electric Company (HEC) B. China Light & Power (CLP)	The emission factor will be specified according to the power company selected

Table 6: Non-numerical inputs for refurbishment in privately-occupied area

Item	**Options (fixtures that are already in place)**	**Rules for selecting solutions**
Fluorescent	A. T8 or T12 fluorescent B. T5 fluorescent	If A is selected, replacement with T5 is applicable
Ballast	A. Magnet ballast B. Electronic ballast	If A is selected, replacement with electronic ballast is applicable
Light bulb	A. Incandescent bulb B. Compact fluorescent lighting (CFL) C. LED lighting	If A is selected, replacement with CFL and LED is applicable
Water heater	A. Electricity storage heater B. Others	If A is selected, reduce the storage temperature of water heat is enabled
Cooker	A. Gas stove B. Induction cooker	If A is selected, replacing with induction cooker is applicable
Stopping draughts	A. Enabled B. Disabled	Enable or disable the use of draught proofing
Power company	A. Hongkong Electric Company (HEC) B. China Light & Power (CLP)	The emission factor will be specified according to the power company selected

Table 7: Profile of the interviewees

Interviewee ID	***Position***	***Organization***
G1	Maintenance surveyor	Government
G2	Senior building service engineer	Government
G3	Building service engineer	Government
C1	Executive Director	Consultant
A1	Associate Professor	Academic
A2	Assistant Professor	Academic

Table 8: Scope of the privately-occupied and common areas

Name	***Scope***	***Example***	***Refurbishment initiator***	
			Private buildings	*Public buildings*
Private-occupied area	The area inside a unit	Living room, bedroom, kitchen, bathroom	Owner	Tenant
Common area	The areas except for all the units	Stair cases, corridors, lift lobbies	Owners' corporations	Government

Table 9: Results of validation

Criteria	***Rating of interviewees***						***Mean***
	G1	*G2*	*G3*	*C1*	*A1*	*A2*	
Proposed solutions							
Comprehensiveness	5	4	4	4	4	4	4.17
Implementability	4	4	4	3	2	3	3.33
Assessment methods							
Accuracy	4	3	3	4	3	3	3.33
Effectiveness	4	4	4	5	4	4	4.17
System interface							
User-friendliness	4	3	4	3	4	3	3.50