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Developing a decision aid for selecting low-carbon refurbishment solutions for multi-story residential buildings in subtropical cities

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6

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

9

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

18

19 **ABSTRACT**

20

21 This paper describes the development of a prototype systematic web-based decision aid for
22 selecting low-carbon refurbishment solutions for multi-story residential buildings in high-
23 density subtropical cities, with special reference to Hong Kong. 88 potential general
24 sustainable refurbishment approaches are identified by a comprehensive literature review, later
25 narrowed down to 39 considered to be relevant to Hong Kong's climatic condition and building
26 characteristics and then to 17 solutions for common areas and 14 for private-occupied areas
27 after interviewing the industry experts and verification by questionnaire survey of occupants.
28 A set of methods is then established through literature review and energy simulation based on
29 a case study, to calculate the CO₂ emission reductions achievable. The system is then
30 described, which includes a set of criteria for identifying *individual* applicable refurbishment
31 solutions, methods of calculating CO₂ emission reductions and parameter input / output and
32 user interface design for a particular building. Finally, a validation process involving industry
33 experts is followed to ascertain the system's practical usefulness and some possible refinements
34 for implementation.

35

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

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42 1. Introduction

43

44 The building sector is responsible for 40% of energy consumption and 30% of GHG
45 emissions all over the world [1]. Taking into account the massive growth of new construction
46 and the large number of inefficient existing buildings, carbon emissions from the building
47 sector will more than double in the next 15 years if the business-as-usual scenario continues
48 [1]. In developed countries and regions such as UK and Hong Kong, the ratio of new to old
49 buildings is lower than 4% each year [2]. The existence of a huge number of inefficient
50 existing buildings will compound the GHG emissions of a city and efforts to mitigate the
51 carbon intensity of existing buildings are therefore indispensable [3,4]. To explore the options
52 possible, a great number of sustainable refurbishment approaches have been developed for both
53 residential buildings [5,6,7] and non-residential buildings [8,9,10]. The quantification of
54 emission reductions resulting from these approaches remains an area of interest to research
55 scientists [11,12] and provides support for studies of decision making for sustainable
56 refurbishment, e.g. Jaggs & Palmer [13], PRUPIM Developments [14], Kylili *et al.* [15], etc.

57

58 Hong Kong has set a goal to mitigate carbon intensity by 50-60% of the 2005 level by
59 2020 [16] but until now, many of its research projects have been directed at enhancing the
60 energy efficiency of offices and commercial buildings [17]. Exploration of suitable
61 approaches to lower the energy consumption of residential building stocks remains relatively
62 sparse, and mainly focuses on the improvement of insulation [18], glazing systems [19,20] and
63 air-conditioning [21,22]. Some pilot studies have been undertaken of the energy performance
64 of local residential buildings, e.g. in energy audit and analysis [23,24], in energy saving
65 measures [25], and on building energy use models [26].

66

67 Hong Kong is a densely populated city, and over 90% of the people live in high-rise
68 apartments, usually of 10-30 stories [24]. The aim of the research, therefore, was to develop
69 a prototype systematic decision aid for selecting low-carbon sustainable refurbishment
70 solutions for multi-story residential buildings in Hong Kong. This involved identifying the
71 sustainable refurbishment solutions available, developing a set of methods for assessing the
72 CO₂ emission reductions of each solution; establishing a systematic system to select the most
73 suitable solutions based on building parameters specified by users; and validating and/or
74 improving it in consultation with industry practice.

75

76

77 **2. Literature review**

78

79 *2.1. Overview of sustainable refurbishment*

80

81 A great number of sustainable techniques have been developed to provide options for the
82 refurbishment of residential buildings [5,27], commercial buildings [8,9] and other types of
83 buildings [28]. Many approaches for lowering operational energy consumption have also
84 been explored, such as by installing wall insulation [18], improving window glazing systems
85 [19,20] and enhancing the performance of air-conditioners [21,22].

86

87 With increasing attention on energy performance in the residential sector, some pilot
88 studies have been conducted by researchers e.g. EST [27], CPA [5], Thorpe [6], Burton [29]
89 and Hakkinen *et al.* [11]. These, together with useful findings concerning sustainable
90 refurbishment [2], relevant guidelines [3] and the systems / tools / frameworks for sustainable
91 decision making [14], provide a solid basis for compiling a set of sustainable refurbishment
92 methods. However, these existing sustainable refurbishment approaches have been

93 developed for specific contexts, with EST [27] and CPA [5], for instance, focusing on buildings
94 in West European countries; Burton's [29] work is mainly based on single or multi-family
95 dwellings; and Baker's [8] studies non-residential buildings.

96

97 In a typical subtropical city such as Hong Kong, the hot and humid summers result in the
98 significant use of air-conditioners [30]. This, together with the high demand for housing due
99 to intensive population are the two fundamental causes of high and increasing electricity
100 consumption for residential buildings in Hong Kong [18,20,30]. Space cooling is needed for
101 7 months a year [31] and around 90% of residential units have installed air-conditioners, the
102 average number of installations being about two per unit [23].

103

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

111

112 *2.2. Decision support for sustainable refurbishment*

113

114 Despite the great number of available sustainable refurbishment solutions on the market,
115 selecting the best refurbishment approach remains difficult, as such selection is a multi-
116 objective optimization problem subject to various constraints and limitations, such as project
117 target, budget, building services type and efficiency, and building envelopes [34]. Although
118 financial benefit is regarded as the primary criteria for sustainable refurbishment, optimal

119 solutions to be considered should include other related factors, e.g. technical factors, carbon
120 emissions, environmental considerations, policy of the government, and social factors. [34,35].
121 In brief, the aim of decision making in sustainable refurbishment is to maximize the cost-
122 effectiveness of a refurbishment project in relation to energy conservation while maintaining
123 satisfactory service levels and acceptable user comfort, under the particular constraints in
124 operation [34]. Moreover, as the requirements of input data and the reliability of results may
125 vary significantly due to different levels of uncertainty under different assumptions [34],
126 selecting or developing a suitable model whose uncertainty level is consistent with a particular
127 project situation is essential for maximizing its chance of success. To this end, Ma *et al.* [34]
128 provide an introduction to the key steps in decisions for sustainable refurbishment projects,
129 with performance according to various solutions being analyzed quantitatively using various
130 approaches such as by employing energy models, economic analysis tools and risk assessment
131 methods [34].

132

133 Sustainable refurbishment assessment is a vitally important aspect of this and has been
134 intensively studied throughout the process of refurbishment projects. Examples include
135 studies of building energy audits and surveys [13,28], building performance assessment and
136 diagnostics [36], quantification of building energy conservation [12,37], as well as economic
137 analyses [38], risk assessment [39] and the measurement and verification of energy savings
138 [40].

139

140 Generally, it is usual to treat embodied energy and ongoing energy consumption separately,
141 where the embodied emissions of materials include the GHGs emitted in manufacturing,
142 transportation, construction process, and demolition [41]. Previous research has shown that
143 the amount of direct GHG emission is proportional to the amount of energy consumption [42]
144 involved in these processes. There is, however, no direct relationship between the amounts

145 of embodied carbon and embodied energy due to GHG emitted in the inherent process of
146 forming materials [43]. Chen *et al.* [41], for instance, adopt multiple data sources of energy
147 consumption in the manufacturing phase, and analyze the energy consumed in transportation
148 by determining the proportion of materials imported from different countries and their
149 corresponding distances from Hong Kong, Two carbon audit toolkits have also been developed
150 to assess embodied GHG emissions for small and medium enterprises [44] and households [45]
151 in Hong Kong.

152

153 As the quantification of energy savings plays an essential role in decision making for
154 sustainable building refurbishment [34], considerable research has been conducted in this area.
155 Ongoing energy savings from building refurbishment are frequently assessed by simulation
156 tools, such as in the application of insulation layers [31,35], upgrading window glazing
157 [18,19,20], and improvements in sealing against air leakages [46]. Rysanek & Choudhary
158 [47] establish a new building physics and energy supply system simulation engine for analyzing
159 the effects of various carbon-reducing retrofit options, while Yalcintas [48] estimates the
160 difference in energy consumption between pre-retrofit and post-retrofit scenarios based on
161 Artificial Neural Networks (ANN).

162

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

171 for calibrating whole building energy models, which can be used to estimate the energy savings
172 of different refurbishment approaches.

173

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

184

185

186 **3. Methodology**

187

188 *3.1. Identification of sustainable refurbishment solutions*

189

190 88 existing sustainable refurbishment solutions were identified from the literature, and a
191 desktop study was conducted to identify the solutions most relevant to the local situation. A
192 series of semi-structured interviews was then conducted with experienced industry experts
193 representing different stakeholder groups such as government, consultants, private developers,
194 and academics holding senior positions in their organizations to learn the applicability of the
195 proposed refurbishment solutions. The responses from the interviews were coded,

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

198

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

206

207 Finally, of the 88 sustainable refurbishment approaches identified, 49 were considered
208 irrelevant to the Hong Kong climatic condition and building characteristics; another 8 methods
209 were eliminated after interviewing the industry experts, and the occupants' acceptance of the
210 solutions for private-occupied areas was confirmed from the questionnaire survey. This
211 resulted in the identification of 17 sustainable refurbishment solutions for common areas and
212 14 solutions for private-occupied areas.

213

214 *3.2. Assessment of emission reductions*

215

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

221

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

229

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

248

249 3.3. *System development process*

250

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

258

259 < *Figure 1* >

260

261 3.4. *Validation*

262

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

271

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273 **4. Development of the system**

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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

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

307

308 < *Table 1* >

309 < *Table 2* >

310 < *Table 3* >

311 < *Table 4* >

312

313 Non-numerical input variables and logical arrangements

314

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

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< *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.

351 4.3. Programming

352

353 Framework of the web application

354

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

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

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

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

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

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

368

369 < *Figure 3* >

370

371 Process of programming

372

373 In the development process of the web application, a database was first built to define the
374 attributes of different types of data, e.g. the power used by, and number of units of, each
375 appliance. Then the calculation methods and the logical rules for enabling / disabling the
376 applications of the sustainable refurbishment solutions were coded using Java language. A

377 system interface was designed to provide the input and output and the CRUD (create, read,
378 update, and delete) operations were also programmed at this stage. Finally, after several
379 debugging sessions, the prototype system was released to a limited number of users for
380 validation purposes.

381

382 *4.4. System operation flow*

383

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

388

389 < *Figure 4* >

390

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

392

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

396

397 < *Figure 5* >

398

399 Step 2: Input the building parameters

400

401 Fig. 6 shows the first part of the input interface, which is for collecting basic project
402 information. This information is not involved in the emission assessment. The second part

403 of input is presented in Fig. 7, which contains the numerical and non-numerical items identified
404 earlier.

405

406 *< Figure 6 >*

407 *< Figure 7 >*

408

409 Step 3: Display the results

410

411 Fig. 8 shows the output results of the system. The upper table provides a list of
412 sustainable refurbishment solutions ranked in ascending order of refurbishment levels together
413 with the energy saving and CO₂ emission reduction values for each solution. In the lower
414 table, the sum of total energy and emission performance for each refurbishment level are
415 determined and exemplified.

416

417 *< Figure 8 >*

418

419 *4.5. Validation*

420

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

423

424 *< Table 7 >*

425

426 After the short presentation the interviewees spent 10 minutes validating the sustainable
427 refurbishment solutions (Table 8), the methods of assessing emission reductions (Tables 1 and
428 4) and the program interface. Each interviewee rated the system in terms of its

429 *comprehensiveness* (how comprehensive are the proposed refurbishment solutions,
430 *implementability* (whether the proposed solutions can be implemented in real projects),
431 *accuracy* (how accurate are the estimated emission reductions); *effectiveness* (whether the
432 system can make improvements in sustainable refurbishment) and *user friendliness*
433 (understandability of the interface and ease of operation). Table 9 shows the results, with
434 scores on a five-point scale from 1 (“fail”) to 5 (“excellent”).

435

436 < *Table 8* >

437 < *Table 9* >

438

439 Comments

440

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

453

454

455 5. Conclusions

456

457 Despite the fact that much experience of sustainable refurbishment has been accumulated
458 in other regions, the climatic condition and building characteristics of high-density subtropical
459 cities such as Hong Kong renders a portion of this inapplicable to the local situation. This
460 paper helps to address this problem by developing a list of suitable sustainable refurbishment
461 solutions for multi-story residential buildings in Hong Kong. The developed solutions form
462 a solid basis for future research into sustainable refurbishment, with consideration of various
463 aspects such as cost, human behavior, policy and decision support. A particular contribution
464 is the system boundary method and calculation methods used to overcome the difficulties
465 involved in determining the CO₂ produced for each sustainable refurbishment solution over the
466 building life cycle.

467

468 A major practical advantage of the system is the simple building parameter input required
469 of lay users. As emission reductions are considered to be one of the most important factors
470 in sustainable refurbishment, the developed system can play an essential role in selecting the
471 best sustainable refurbishment solutions for residential buildings in Hong Kong and provides
472 the basis for the development of similar such aids in other high-density subtropical cities, thus
473 helping promote the development of sustainable refurbishment and the achievement of
474 associated CO₂ emission reductions in general.

475

476 A limitation of the empirical results of the work is that they are restricted to high-rise
477 residential buildings based on a case study of a typical Hong Kong public housing scheme.
478 However, the *method* used in developing the system is has no such restrictions and should be
479 capable of being followed for any form of construction work anywhere. The potential for
480 future research is to extend the current sole focus on energy and carbon emissions savings to

481 other factors such as cost, human intervention, environment, and culture. Similarly, the
482 current restriction to operational and the total embodied carbons can be extended to other
483 phases of a building's life cycle, such as construction and demolition, although these are
484 generally considered to make a relatively small contribution. Finally, although the system has
485 been validated by industry experts, which is effective for evaluating the refurbishment solutions
486 and system interface, experiments or in-depth data analyses will provide a better validation of
487 this part of the overall research outcome.

488

489

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491

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494

495

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498

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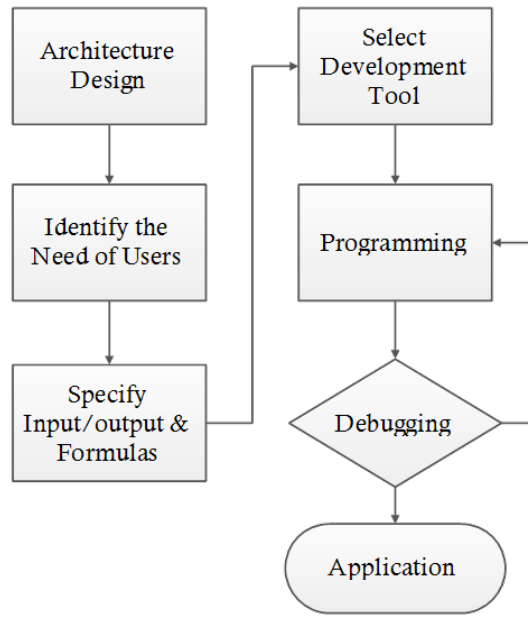
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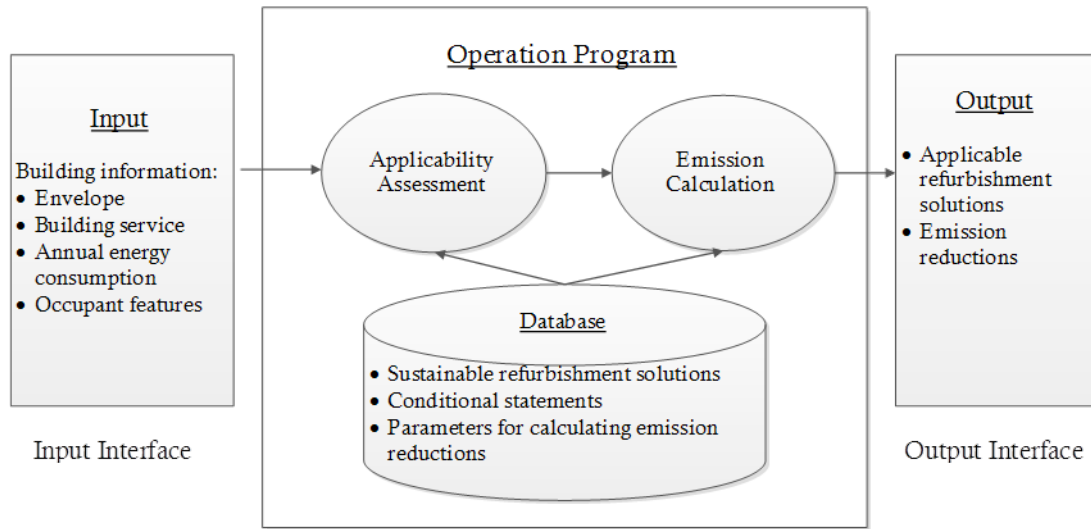
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Figure 1: System development process

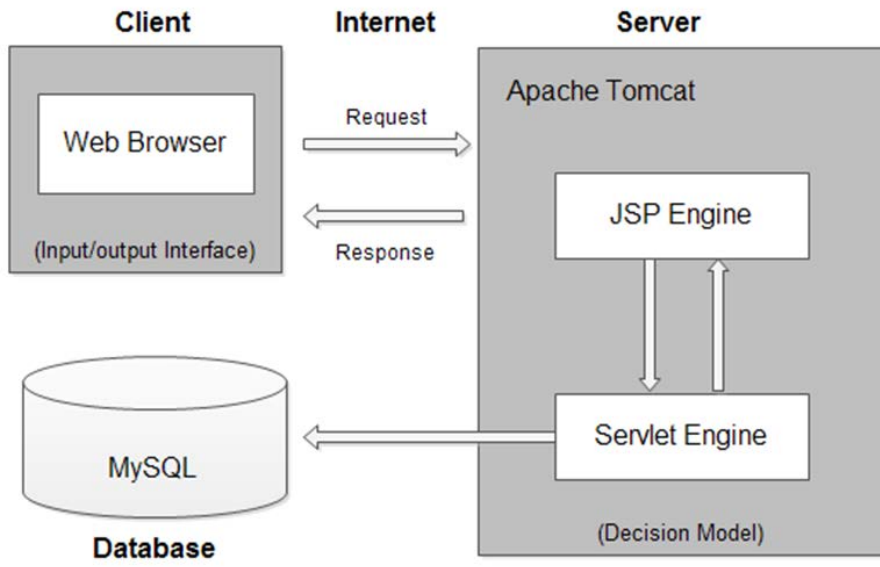
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Figure 2: System architecture

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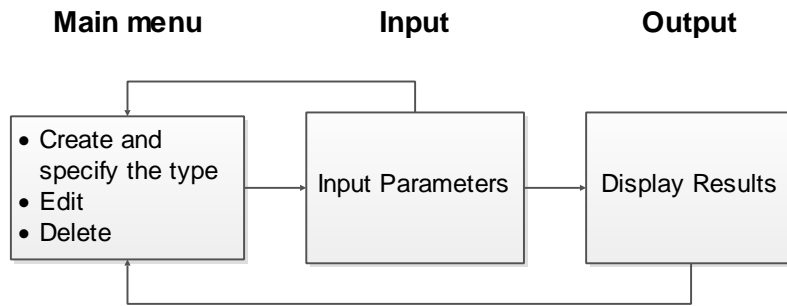
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Figure 3: Framework of the web application

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Figure 4: Operation flow

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Figure 5: Main menu

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The screenshot shows a web browser window with the address bar displaying 'localhost:8080/CBR/cbr/toAddHec'. The page title is 'add HEC'. The form is organized into sections:

- Basic Information:** This section contains two columns of input fields. The left column includes 'Case Name', 'Bid_Owner', 'Bid_Age', 'Bid_Location/Region', 'Materials Supplier', 'Refurbishment Approach' (set to 'Measures-based'), and 'Cost'. The right column includes 'Bid_Type' (set to 'Commercial'), 'Bid_Space', 'Service Provider', 'Equipment Supplier', 'Funding Support' (set to 'False'), and 'Objectives Achieved' (set to 'All'). Below these fields is a large empty text area labeled 'Objectives:'.
- Windows:** This section is located at the bottom of the form and includes 'Type of window glazing' (set to 'Clear glazing') and 'Area of the window(m2)'.

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Figure 6: Input of basic project information

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The screenshot shows a web browser window with a form titled "toAddHec". The form is organized into several sections, each with a heading and multiple input fields:

- Windows:** Includes a dropdown for "Type of window glazing" (set to "Clear glazing") and a text input for "Area of the window (m2)".
- Flourescent:** Includes a dropdown for "Type of flourescent" (set to "T8 or above"), a text input for "Number", and text inputs for "Power (W)" and "Daily operational hours".
- Light bulb:** Includes a dropdown for "Type of light bulb" (set to "Incandescent bulb"), a text input for "Number", and text inputs for "Power (W)" and "Daily operational hours".
- Water heating:** Includes a dropdown for "Type of water heating" (set to "Electrical storage heater") and a text input for "Storage temperature (Celcius degree)".
- Air-con:** Includes text inputs for "Set-point of air-conditioner (Celcius degree)" and "Number of air-conditioner".
- Others:** Includes dropdowns for "Type of cooker" (set to "Gas stove"), "Efficiency label of showerhead" (set to "1"), and "Draught-proofing devices" (set to "None"). It also includes a dropdown for "Type of ballast" (set to "Magnet ballast") and a dropdown for "Everage energy label level of the appliance" (set to "1").
- Annual consumption:** Includes text inputs for "Number of occupants", "Electricity consumption (kWh)", "Water consumption (m3)", and "Total carbon emission (kg)". It also includes dropdowns for "Power company" (set to "HEC") and text inputs for "Gas consumption (MJ)" and "Total energy consumption (MJ)".

The form is styled with a light background and orange borders around the input fields. The browser's address bar shows "localhost:8080/CBR/cbr/toAddHec".

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Figure 7: Numerical and non-numerical inputs

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The screenshot shows a web browser window with the address bar containing the URL: localhost:8080/CBR/cbr/calculate?id=4a3de7a8468f082c01468f09547a0000&name=Hec. The page title is 'Manager HecResult'. The main content area is titled 'Solutions of Sustainable Refurbishment' and contains a table with 6 columns: Level of Refurbishment, Refurbishment methods, Energy saving (kWh), Percentage of Energy Saving, CO2 Emission Reduction (kg), and Percentage of Emission Reduction. Below this table is another section titled 'Outcome of Different Level of Sustainable Refurbishment' with a similar table structure. At the bottom of the second table, there is a 'return' link.

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 fluorescent	0.0	0%	0.0	0%
2	LED lighting	99.68	0%	83.73	2.34%
2	Compact fluorescent 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](#)

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Figure 8: Results display

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

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

Lift with power regeneration system	$E = \sum E_0 \times P \times 0.2$ <p>where E = annual energy saving (kWh); E₀ = original annual energy consumption of lifts (kWh); the method of calculating E₀ is shown in Table 2.</p>	[59]
Lifts with advanced VVV-F control system	$E = \sum E_0 \times P \times 0.4$ <p>where E = annual energy saving (kWh); E₀ = original annual energy consumption of lifts (kWh); the method of calculating E₀ is shown in Table 2.</p>	[60]
Permanent magnet synchronous lift motor	$E = \sum E_0 \times P \times 0.2$ <p>where E = annual energy saving (kWh); E₀ = the original annual energy consumption of lifts (kWh); the method of calculating E₀ is shown in Table 2.</p>	[59]
Green roof	$E = E_{total} \times 0.1$ <p>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</p>	[61]
Rearrangement of lighting circuits to fully utilize daylight corridors	$E = \sum P \times N \times H \div 1000$ <p>where E = annual energy saving (kWh); P = power of lightings (W); N = number of lightings reduced; H = reduced annual operation hours</p>	N.A. (Direct calculation)
Photovoltaic panels	$E = A \times 120 \times 0.8 \div \cos 22^\circ = A \times 104.3$ <p>where E = annual energy generation (kWh); A = roof area (m²)</p>	[62]
Time switches	$E = \sum P \times N \times H \div 1000$ <p>where E = annual energy saving (kWh); P = power of lightings (W); N = number of lightings under control; H = reduced annual operation hours</p>	N.A. (Direct calculation)
Replace water pumps with higher efficiency one	$E = \sum P \times N \times H \times 0.02$ <p>where E = annual energy saving (kWh); P = power of pumps (kW); N = number of pumps; H = annual operation hours</p>	[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 (°C); 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]

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Table 2: Method of calculating the annual consumption of lifts

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

768 *Source: Nipkow & Schalcher, 2006 [70]*

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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 CO₂)	Embodied carbon emission (kg CO₂)	Annual emission reduction (kg CO₂)	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
<i>Total</i>	<i>1895</i>	<i>1496</i>	<i>0.02</i>	<i>1496</i>	<i>47.07</i>

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Table 4: Numerical inputs for emission estimation

<i>Common area</i>		<i>Private-occupied area</i>
Lighting	Daylight sensors	Fluorescent
<i>Power (W)</i>	<i>Power (W)</i>	<i>Power (W)</i>
<i>Number</i>	<i>Number</i>	<i>Number</i>
<i>Daily operation hours</i>	<i>Reduced operation hours</i>	<i>Daily operational hours</i>
Lifts	Motion sensors	Light bulb
<i>Power (kW)</i>	<i>Power (W)</i>	<i>Power (W)</i>
<i>Height of building (m)</i>	<i>Number</i>	<i>Number</i>
<i>Number</i>	<i>Reduced operation hours</i>	<i>Daily operational hours</i>
Pumps	Roof area (m ²)	Hot water storage temperature (°C)
<i>Power (kW)</i>	Annual energy consumption	Set-point of air-conditioner (°C)
<i>Number</i>	<i>Public zone (kWh)</i>	Number of occupants
Time switch	<i>Private zone (kWh)</i>	Annual consumption
<i>Power (W)</i>		<i>Electricity (kWh)</i>
<i>Number</i>		<i>Gas (KJ)</i>
<i>Reduced operation hours</i>		<i>Water (m³)</i>

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

<i>Item</i>	<i>Options (fixtures that are already in place)</i>	<i>Rules for selecting solutions</i>
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

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

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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

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796 *Table 7: Profile of the interviewees*

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<i>Interviewee ID</i>	<i>Position</i>	<i>Organization</i>
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

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

<i>Name</i>	<i>Scope</i>	<i>Example</i>	<i>Refurbishment initiator</i>	
			<i>Private buildings</i>	<i>Public buildings</i>
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

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Table 9: Results of validation

Criteria	Rating of interviewees						Mean
	<i>G1</i>	<i>G2</i>	<i>G3</i>	<i>C1</i>	<i>A1</i>	<i>A2</i>	
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

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