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# **A multi-objective approach for optimal prioritization of energy efficiency measures in buildings: Model, software and case studies.**

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## **Abstract**

Buildings are responsible for some 40% of the total final energy consumption in the European Union and about 40% of the world's primary energy consumption. Hence, the reduction of primary energy consumption is important for the overall energy chain. The scope of the current work is to assess the energy efficiency measures in the residential and small commercial sector and to develop a methodology and a software tool for their optimal prioritization.

The criteria used for the prioritization of energy efficiency measures in this article are the primary energy consumption and the initial investment cost. The developed methodology used is generic and could be implemented in the case of a new building or retrofitting an existing building. A multi-objective mixed-integer non-linear problem (MINLP) needs to be solved and the weighted sum method is used. Moreover, the novelty of this work is that a software tool has been developed using 'Matlab<sup>®</sup>' which is generic, very simple and time efficient and can be used by a Decision Maker (DM). Two case studies have been developed, one for a new building and one for retrofitting an existing one, in two cities with different climate characteristics. The building was placed in Edinburgh in the UK and Athens in Greece and the analysis showed that the primary energy consumption and the initial investment cost are inversely proportional.

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33 Keywords: Building energy efficiency, Energy efficiency measures, Multi-objective  
34 optimization

## 35 **1 Introduction**

36

37 The increase of primary energy consumption and the climate change are amongst the biggest  
38 challenges the 21st century faces. In most countries, governments have policies which aim to  
39 reduce primary energy consumption by promoting energy efficiency. Specifically, the  
40 building sector accounts for some 40% of the total final energy consumption in the European  
41 Union and some 40% of the world's primary energy consumption [1], [2]. The European  
42 Commission in order to rationalize the use of energy in buildings and increase energy  
43 efficiency has issued the Energy Performance of Buildings (EPBD) Directive 2002/91/EC and  
44 its recast 2010/31/EU regarding the European energy policy for the energy performance of  
45 buildings and the rational use of energy [3], [4].

46

47 The reduction of energy consumption and especially primary energy consumption will  
48 contribute to the reduction of energy in the total energy chain and increase sustainability in  
49 buildings. Investing in energy efficiency is essential as the overall benefits will outweigh the  
50 initial investment cost. The building sector is large, both in terms of energy consumption but  
51 also in terms of number and type of buildings available. In general, there are two categories of  
52 buildings, namely the existing buildings that might need retrofit actions and the new building  
53 that are going to be built.

54

55 In order to reduce the primary energy consumption in buildings several efficiency measures  
56 can be implemented. These measures can be divided into categories, such as those related to  
57 the building envelope, the energy systems that provide heating, cooling and hot water, the  
58 electrical appliances and the lighting systems and can be found analytically in [5]. Also, there  
59 are energy systems that can provide electricity. Those can be cogeneration units or renewable  
60 energy sources (RES) such as biomass, wind energy and solar energy. Energy efficiency  
61 measures in each category have a different contribution to the reduction of the final and  
62 primary energy consumption and also have an initial investment cost, typically higher than  
63 conventional systems. Furthermore, the building's location plays an important role as the  
64 climate and the available RES in an area might provide different solutions for each case.

65

66 Therefore, a Decision Maker (DM) needs to make a decision between many alternative  
67 choices, which is usually not easy. The DM must take into account several criteria such as  
68 financial or environmental in order to find the optimal solution according to his own  
69 preferences. Although there are many approaches to tackle such problems, in this article a  
70 multi-objective programming approach will be used. The first objective is to minimise the

71 primary energy consumption and the second objective is to minimise the initial investment  
72 cost. A general rule followed states that if the initial investment cost is higher in components  
73 with better energy behaviour, then the primary energy consumption will be lower resulting in  
74 more energy savings. However, it is often the case that a DM does not have unlimited  
75 resources, hence a compromise solution between these two criteria needs to be found. The  
76 main concept of this approach is to allow the DM to propose the efficiency measures that he  
77 is interested in, so as to allow him to find the optimal approaches for each category.

78

79 The paper is structured as follows: Section 2 provides a literature review of research on  
80 energy efficiency measures in buildings. In Section 3 the proposed model is described.  
81 Decision variables, constraints, parameters and objective functions are presented. Section 4  
82 describes the multi-objective optimization approach used to solve the problem. Section 5  
83 presents the developed software tool, which is explained in detail. In Section 6 the performed  
84 case studies for a new building and an existing building under renovation are described and in  
85 Section 7 the results are analysed. Section 8 concludes the paper. Moreover, in Appendix  
86 “A” the equations of the model are shown analytically, in Appendix “B” the proposed  
87 components for the buildings in the case studies are presented and finally, in Appendix “C”  
88 the values of the decision variables for the performed case studies are presented in detail.

89

## 90 **2 Literature Review**

91

92 Calculating energy loads in building and assessing energy efficiency measures has been  
93 researched extensively in the last years. In 2006 Chung *et al.* in [6] performed a study  
94 regarding benchmarking energy efficiency in commercial buildings using multiple regression  
95 analysis. In [7] Wang *et al.* reviewed the energy performance methods for existing buildings.  
96 In their study they quantify energy usage and propose a framework for the categorization of  
97 energy quantification methods for existing buildings. Energy quantification methods are  
98 divided into three categories, namely the calculation-based, measurement-based and hybrid  
99 quantification methods. Regarding calculation-based methods, are further divided into  
100 dynamic methods (use of basic simulation or representative simulation tools) and steady-state  
101 methods (e.g. forward modelling approach or inverse modelling approach). Typical steady-  
102 state methods used for the calculation of thermal performance in buildings are the degree-day  
103 (DD) method, bin method and equivalent full-load hour method. Measurement based methods  
104 are further divided into energy bill-based methods and monitoring-based methods. Finally,  
105 hybrid quantification methods consist of calibrated simulations and dynamic inverse models.  
106 A method for assessing buildings’ energy efficiency using dynamic simulation and

107 experiments has been developed by Pisello *et al.* in [8]. They proposed a methodology for  
108 analysing the thermal performance of buildings using non-dimensional indexes. Another  
109 framework for characterizing energy efficiency measures has been developed by Trianni *et al.*  
110 in [9], which is based on several attributes grouped into six categories, namely economic,  
111 energy, environmental, production, implementation and interaction with other systems.

112

113 The problem of designing low energy buildings and prioritizing the energy efficiency  
114 measures has been approached by many researchers throughout the years. There are many  
115 methods that can be used in order for a DM to make the optimal choice regarding which  
116 energy efficiency measures to choose. Kolokotsa *et al.* [10] analyse the decision support  
117 methodologies that can be used regarding the energy efficiency and management in buildings.  
118 The criteria that can be used in order to support a decision are divided in categories such as:  
119 (a) energy related: primary or final energy consumption, the heating and cooling load,  
120 electricity consumption, embodied energy; (b) cost related: direct cost, initial investment cost,  
121 life cycle cost, net present value and internal return rate of the investment; (c) environmental  
122 related: annual emissions and global warming potential, life cycle environmental potential;  
123 (d) indoor quality related: indoor temperature and humidity, CO<sub>2</sub> concentration, ventilation  
124 rate, daylight availability, noise levels and (e) other criteria such as construction duration,  
125 security etc.

126

127 In [11] Evins performed a review of the computational optimization methods that are applied  
128 to sustainable building design. His analysis shows that there is a growth in the use of  
129 optimization in sustainable building design, and more particular in the use of multi-objective  
130 optimization methods. The dominant optimization method is genetic algorithm. Most of the  
131 studies performed have energy as an objective function, followed by construction cost.  
132 Regarding area of building design, building envelope is the dominant one. Another review  
133 about the simulation-based optimization methods applied to buildings performance was done  
134 by Nguen *et al.* in [12] and revealed that the major drawbacks in these methods are the  
135 complexity of the problems, the high computational cost, the uncertainty of the parameters  
136 and the multi-objective design problems. Also, their results point out that the most used  
137 software packages for building simulations are EnergyPlus and TRNSYS and the most used  
138 optimization platforms are GenOpt and Matlab.

139

140 Mavrotas *et al.* in [13] studied energy planning in buildings taking into account the  
141 uncertainty of fuel costs. They developed a linear programming model with fuzzy parameters  
142 in order to deal with the uncertainties of fuel costs, which then is transformed into an

143 equivalent multi-objective problem. Their analysis is mainly applied to larger energy  
144 consuming buildings where energy investment decisions may be affected significantly.

145

146 Wang *et al.* [14] in 2005 tried to use genetic algorithms in a multi-objective programming  
147 approach for designing green buildings. Their approach was to minimise the life cycle cost  
148 and the life cycle environmental impact, by taking into account the building's design  
149 variables of the building's envelope. In their analysis they used genetic algorithms (GA) but  
150 as those are random the resulted Pareto Front was considered to be the values of the external  
151 population (final solutions). The study showed that optimal values for some variables change  
152 between different Pareto zones. Also, it was shown that the utility structure affects the  
153 environmental performance significantly.

154

155 Chlela *et al.* in [15] introduced a methodology regarding the design of new buildings based  
156 on parametric analysis. This approach requires a design of experiments in order to perform a  
157 statistical analysis on the selected variables, resulting in the modelling of the energy  
158 consumption.

159

160 In 2008, Diakaki *et al.* [1] built a generic methodology based on multi-objective programming  
161 approach, aiming to minimize the primary energy consumption and the initial cost of  
162 acquisition of the materials. The proposed model was limited as the only decision variables  
163 were the window types, the insulations materials and the thickness of the wall. Also, different  
164 multi-objective optimization techniques have been investigated, such as compromise  
165 programming with the Tchebyshev criterion, the global criterion method and the goal  
166 programming method.

167

168 Moreover, Diakaki *et al.* in [16] further developed the proposed methodology in [1]. They  
169 resulted in a more detailed methodology by taking into account all the decision variables  
170 regarding the thermal envelope and the energy systems of the building (except those  
171 producing electricity). The model was based on a multi-objective programming approach  
172 regarding the prioritization of energy efficiency measures in a new building that will be  
173 constructed. The decision criteria that were used were the minimization of the primary energy  
174 consumption, the initial investment cost (cost of construction, acquisition and installation) and  
175 the CO<sub>2</sub> emissions.

176

177 A different approach aiming to optimize the thermal comfort and the energy consumption in a  
178 residential building has been presented by Magnier and Haghic at in [17]. They proposed an  
179 efficient model where the decision variables are related to the thermostat settings, heating,

180 ventilation and air condition system (HVAC) and passive solar design. Their approach was  
181 based on the usage of a multi-objective evolutionary genetic algorithm (NSGA-II) with a  
182 simulation-based Artificial Neural Network (ANN) method.

183

184 Popescu *et al.* in [18] studied the impact of energy efficiency measures on the economic value  
185 of buildings. They assessed investments in energy efficiency measures by measuring the  
186 payback period of investments, which they claim depends on the energy savings and the  
187 added value of the property. However, they recommend that this financial analysis should be  
188 taken into account when there is reliable evidence to support that the real-estate market reacts  
189 to energy performance of the buildings. In [19] Saari *et al.* investigated the financial viability  
190 of energy efficiency measures in a new detached building in Finland. They studied the impact  
191 on the construction costs and the financial viability of eight alternative design concepts.

192

193 Yao in [20] studied energy optimization of building design in apartment buildings. He  
194 introduced EDH index, which measures the energy performance difference between housing  
195 units in order to evaluate proposed measures in design options aiming to reach 50% energy  
196 efficiency improvement. Kusiak *et al.* in [21] performed a study about modelling and  
197 optimization HVAC energy consumption in a typical office building. They used eight data-  
198 mining algorithms to evaluate energy consumption, control settings and a set of parameters  
199 and they constructed four models of energy consumption. They used a single objective  
200 approach that was solved by the particle swarm optimization algorithm.

201

202 Fesanghary *et al.* in [22] proposed a multi-objective optimization model based on harmony  
203 search algorithm. The decision criteria in that methodology were the minimization of the life  
204 cycle cost and the minimization of the carbon dioxide equivalent emissions of the building.

205

206 Asadi *et al.* in [23] used a multi-objective optimisation programming problem trying to  
207 maximize the energy savings and to minimise the retrofit cost, after the refurbishment of a  
208 semi-detached building in Portugal. However, despite the fact that their approach was based  
209 on the Portuguese regulations of building design, it could be transferred and used for other  
210 countries as well.

211

212 In [24] Chantrelle *et al.* developed a multi-criteria optimization tool (MultiOpt) for the  
213 renovation of buildings. MultiOpt has a graphical user interface and has a set of four criteria,  
214 namely energy consumption, thermal comfort, cost and environmental impact. It takes into  
215 account parameters related to control strategies and building envelope. For the optimization  
216 procedure genetic algorithm NSGA-II is used.



217

218 A more recent study was made by Malatji *et al.* in [25] using a multi-objective model aiming  
219 to maximize the energy savings after retrofitting a building and minimise the payback period  
220 of the investment. In this approach the energy savings were not calculated but were taken  
221 from the manufacturers' data. They used compromise programming technique with two  
222 objectives and a genetic algorithm was used to solve the problem. Also, a sensitivity analysis  
223 was performed to investigate uncertainties in parameters such as auditing error of the  
224 facilities, variability of electricity prices, wrong calculation of energy savings, increase of the  
225 initial investment cost, and change of the interest or discount rate.

226

227 Moreover, Hamdy *et al.* in [26] presented an efficient and time-saving simulation-based  
228 optimization method. Their methodology was referring to the nearly-zero-energy building and  
229 cost-optimal solutions of a single-family building in Finland, following the EPBD recast of  
230 2010 [4]. They tried to minimize the primary energy consumption and the difference of the  
231 life-cycle cost between a design option and a reference design for the specific climate zone.

232

### 233 **3 Model Building**

234

235 Diakaki *et al.* in [16] developed a multi-objective decision model for the improvement of  
236 energy efficiency in buildings. In the current work we expand the model presented in [16] by  
237 taking into account the lighting systems, electrical appliances and RES. Also, it is further  
238 expanded to include the case of retrofitting an existing building. Another difference between  
239 our work and [16] is that all the decision variables are considered to be binary. In other words,  
240 we assume predetermined discrete values for the continuous variables of the model in [16]  
241 which is in most cases more realistic (e.g. the thickness of insulation has predetermined  
242 values). In this way we obtain a discretization of the decision space which is appropriately  
243 modelled using binary variables. The basic characteristics of the model are given briefly  
244 below while the full model with all the equations is presented in Appendix "A".

245

#### 246 **3.1 Decision variables**

247

248 The current approach consists of decision variables related to: (1) the building envelope; (2)  
249 the building's energy system; (3) the lighting system and (4) the electrical appliances.  
250 Regarding the building envelope we have decision variables for door type, window type, wall  
251 type with different layers of materials of different type. In other words, each wall type  
252 consists of a number of known layers. The materials of these layers have specific thermal

253 conductivity and thickness. The same holds for the decision variables expressing the ceiling  
254 and the floor type.

255 The building's energy system related decision variables describe the following issues:

- 256 • Heating systems: Provide only heating and can be electrical or non-electrical systems  
257 which are further categorized according to their input fuel;
- 258 • Cooling systems: Provide only cooling (in this approach only electrical systems are  
259 assumed to be available)
- 260 • DHW systems: Provide only hot water. They can be electrical or non-electrical, which  
261 are further categorized according to their input fuel;
- 262 • Heating – cooling systems: Provide both space heating and cooling (only electrical  
263 systems are assumed to be available);
- 264 • Heating – DHW systems: Provide both space heating and DHW supply. They can be  
265 electrical or non-electrical which are further categorized according to their input fuel;
- 266 • Solar collector systems: Supply DHW by utilizing solar energy;
- 267 • Electricity generation systems: Provide electricity using RES.

268

269 The lighting system and the electric appliances are described by appropriate binary decision  
270 variables, each one expressing a specific type.

271

### 272 **3.2 Constraints**

273

274 The constraints of the problem are mainly the energy balances, which means the satisfaction  
275 of the energy demand for heating, cooling, DHW, lighting and electricity supply. Moreover,  
276 in order to satisfy the energy demand the appropriate equipment must be selected. Therefore,  
277 there are constraints regarding the selection of one equipment to satisfy the energy demand  
278 for the respective category. In addition, there are constraints where one piece of equipment is  
279 selected in case the same equipment can be used for multiple purposes (e.g. a heat pump for  
280 both heating and cooling). Regarding the investment cost, it is calculated depending the  
281 selected equipment for each category. The constraints can be seen in detail in Section A.2 in  
282 Appendix "A".

283

### 284 **3.3 Parameters**

285

286 The parameters of the model are in general meteorological data, technical coefficients,  
287 demand data, efficiencies, standard dimensions and costs which are required in the model's  
288 constraints and objective functions, and most of which need to be insert by the DM.

289

290 In order to calculate the energy demand air temperature, solar radiation, water temperature,  
291 number of people leaving in the house and dimensions of the building envelope are necessary.  
292 Also, for the calculation of primary energy consumption for lighting and electrical appliances,  
293 the number and operational hours of lamps and appliances are required. More technical  
294 parameters such as efficiency coefficients of the selected equipment and of the electricity grid  
295 are also necessary for the calculations. Moreover, the cost of the components is required for  
296 the calculation of the total investment cost. All the parameters are presented analytically in  
297 Appendix “A”.

298

### 299 **3.4 Objective functions**

300

301 In this model there are two objective functions: (a) minimization of the total annual primary  
302 energy consumption or maximization of total annual primary energy savings and (b) the  
303 minimization of the total investment cost for the interventions:

304  $g_1(\mathbf{x})$ : Total annual primary energy consumption or total annual primary energy savings.

305  $g_2(\mathbf{x})$ : Total Investment Cost

306

307 The primary energy consumption is the sum of energy consumption for heating, cooling,  
308 DHW, lighting and electrical appliances. In this work, heating and cooling loads are  
309 calculated using the DD method (for more details see [7], [27]). For the case of retrofitting an  
310 existing building the methodology is similar to that of a new building. However, in this case  
311 the objectives would be to achieve maximum primary energy savings with minimal initial  
312 investment cost. Therefore, the primary energy consumption of the existing building before  
313 any retrofit action must be calculated. The objective functions are described in more detail in  
314 Section A.3 of Appendix “A” for both cases, namely, the case of a new building and the case  
315 of retrofitting an existing one.

316

## 317 **4 Multi-objective Optimization**

318

319 As the name suggests, multi-objective (or multi-criteria) optimization involves optimization  
320 in the presence of more than one (usually conflicting) objective functions. Multi-objective  
321 optimization problems arise in a variety of real word applications and the need for efficient  
322 and reliable methods is increasing. The main difference between single and multi-objective  
323 optimization is that in the case of latter, there is usually no single optimal solution, but a set of

324 equally good alternatives with different trade-offs, also known as Pareto-optimal (or non-  
 325 dominated or efficient) solutions. In the absence of any other information, none of these  
 326 solutions can be said to be better than the other. Usually a decision maker is needed to  
 327 provide additional preference information and to identify the “most preferred” solution.  
 328 Depending on the paradigm used, such knowledge may be introduced before, during or after  
 329 the optimization process. Multi-objective optimization thus has to combine two aspects:  
 330 optimization and decision support.

331

332 In our case the problems defined in Equation (A.100) and in Equation (A.102) is a multi-  
 333 objective programming problem which fall into the category of mixed-integer non-linear  
 334 programming problems (MINLP). For the solution of this kind of problems we will first  
 335 calculate a representation of the Pareto set and then we will select the most preferred among  
 336 the Pareto optimal solutions. For the calculation of adequate representations of the Pareto set  
 337 a straightforward method is the weighting method [28]–[30].

338

339 Therefore, equation (A.100) is modified as follows:

$$340 \quad \min [u(g_1(\mathbf{x}), g_2(\mathbf{x}))] = p_1 \left( \frac{g_1(\mathbf{x}) - g_{1\min}}{g_{1\max} - g_{1\min}} \right) + p_2 \left( \frac{g_2(\mathbf{x}) - g_{2\min}}{g_{2\max} - g_{2\min}} \right) \quad (1)$$

341

*Subject to*

342

Constraints: (A.1) - (A.99)

343 Where,

344  $\mathbf{x}$ : a vector with the decision variables.

345  $g_1(\mathbf{x})$ : Total annual primary energy consumption

346  $g_2(\mathbf{x})$ : Total investment cost

347  $g_{1\min}$  and  $g_{2\min}$ : are the values of the criteria of (A.100) when they are optimized  
 348 independently.

349  $p_1$  and  $p_2$ : weight coefficients that reflect the relative importance of the two criteria, allowing  
 350 the DM to take into account his personal preferences. The following condition for the weights  
 351 must hold:

$$352 \quad p_1 + p_2 = 1 \quad (2)$$

353

354  $g_{1\max}$  and  $g_{2\max}$ : are the “nadir” (=worst) values of the criteria of Equation (A.100) and they  
 355 are obtained from the payoff table (minimization of  $g_1$  provides  $g_{2\max}$  and vice versa,  
 356 minimization of  $g_2$  provides  $g_{1\max}$ ). The denominator ( $g_{k\max} - g_{k\min}$ ) is necessary as range  
 357 equalization factor in order to provide a normalization of the objective functions. In this way

358 the weight coefficients are more meaningful and they are not influenced by differences in the  
359 objective functions' scale or by the range of the objective functions.

360

361 As we told, for multi-objective optimization problems there is not a single solution. Hence the  
362 concept of Pareto optimality is used which is defined as a set of solutions that belong in a pre-  
363 set classification of an optimal solution. The weighting method is a scalarization method  
364 which combines the two functions in one, allowing a DM to express his preference a priori or  
365 a posteriori and compromise between the two criteria [17]. If the weight coefficients are  
366 greater than zero then Equation (1) is sufficient for Pareto optimality [31].

367

368 In the case of retrofitting an existing building where the first objective ( $g_1$ ) is to maximize the  
369 energy savings equation (A.102) is modified as follows:

$$370 \quad \min [u(g_1(\mathbf{x}), g_2(\mathbf{x}))] = p_1 \left( \frac{g_{1\max} - g_1(\mathbf{x})}{g_{1\max} - g_{1\min}} \right) + p_2 \left( \frac{g_2(\mathbf{x}) - g_{2\min}}{g_{2\max} - g_{2\min}} \right) \quad (3)$$

371

*Subject to*

372

Constraints: (A.1) - (A.99), (2)

373 Where,

374  $g_1(\mathbf{x})$ : Total annual primary energy savings.

375  $g_2(\mathbf{x})$ : Total investment cost.

376

## 377 **5 Software Tool**

378

379 The methodology described in Section 3 has been used to develop a software tool for the  
380 optimal prioritization of energy efficiency measures for a new and an existing building. The  
381 software tool has been developed using 'Matlab<sup>®</sup>' and 'Microsoft Excel<sup>®</sup>'. The novelty of this  
382 software tool is that it has the advantage of being generic and not depending on the number of  
383 components in a building (e.g. number of doors, number of windows, number of walls etc). A  
384 'Microsoft Excel<sup>®</sup>' spreadsheet contains all the relevant data for the analysis, i.e. the climate  
385 data, building's characteristics and the proposed energy efficient measures.

386

387 In this software tool the following assumptions have been made: (a) only four categories of  
388 electrical appliances have been used, which are: a television, an electric cooker, a refrigerator  
389 and a washing machine; (b) only three alternative choices can be proposed for each decision  
390 variable, hence the total number of decision variables is sixty three (63) and (c) only the case

391 of solar PV has been examined in the category of RES systems that are used to provide  
392 electricity.

393

394 It is noted that the electrical energy output of a photovoltaic system is equal to [32]:

$$395 \quad Q_{pv} = A_{pv} n_{pv} PR_{pv} F_{s,pv} I_{SL} \quad (4)$$

396 Where,

397  $A_{pv}$ : the area of the photovoltaic array ( $m^2$ )

398  $n_{pv}$ : efficiency of the panel (%)

399 PR: performance ratio expressing the losses of the system (circuit, battery, inverter) (%)

400  $F_{s,pv}$ : shading factor (%)

401

402 In order to solve this multi-objective problem ‘BONMIN’ algorithm has been used which is  
403 suitable for solving convex MINLP problems [33]. As ‘BONMIN’ is not implemented in  
404 ‘Matlab<sup>®</sup>’ the ‘OPTI TOOLBOX’ has been used, which is an open-source software that can  
405 be implemented in ‘Matlab<sup>®</sup>’ and has many optimization solvers available [34].

406

407 In order to use the software tool a DM must know how to use the necessary script files and  
408 needs to have ‘Matlab<sup>®</sup>’ and the ‘OPTI TOOLBOX’ installed. The software tool can perform  
409 all the necessary calculations and export the results in a ‘Microsoft Excel<sup>®</sup>’ file. The weight  
410 factors pairs that are used are fixed and equal to:  $p_1=1$  and  $p_2=0$  to  $p_1=0$  and  $p_2=1$  with step  
411 equal to 0.05. The reasons why the weight factors pairs are fixed a priori is to provide the full  
412 Pareto front to a DM, allowing him to examine all the optimal solutions.

413

414 The results obtained by using the software tool are all the values of the minimization of  
415 equation (1), the primary energy consumption, the initial investment cost and the values of the  
416 decision variables for each working pair of weight coefficients. Moreover, for further  
417 analysis, the software tool can be used to export the results of energy demand and primary  
418 energy consumption of each category for each month by using the respected script file.

419

420 Similarly to the provided software tool for the case of a new building described in the  
421 previous section, and based on the methodology described in Section 3 a software tool has  
422 been developed for the optimal prioritization of energy efficiency measures for the case of  
423 retrofitting an existing building.

424

425 Its features are similar to the software tool for the new building. Moreover, due to the  
426 constraints described in A.3.2 (i.e. no proposed wall, floor or ceiling structures) the total

427 number of decision variables is reduced to fifty four (54). Instructions regarding the usage of  
428 the software tool and the spreadsheet are available within.

429

430 An additional assumption for the case of retrofitting an existing building is that the DM is  
431 interested to make changes in all the categories of energy efficiency measures. This means  
432 that the software tool will provide solutions for each set of the proposed components. The  
433 software tool can perform all the necessary calculations and it can export the results in a  
434 ‘Microsoft Excel<sup>®</sup>’ file. The results obtained by using the software tool are all the values of  
435 the minimization of equation (3), the maximization of the primary energy consumption  
436 savings, the minimization of the initial investment cost and the values of the decision  
437 variables for each working pair of weight coefficients. Moreover, for further analysis, the  
438 software tool can be used to export the results of energy demand and primary energy  
439 consumption of each category for each month before and after the retrofit actions.

440

441 Also, it is noted that in this software tool some variables are considered to be constant and are  
442 presented in Table 1.

443

Parameters	Value [27]
$ACH$ ( $h^{-1}$ )	1.5
$\rho_{air}$ ( $kg/m^3$ )	1.2
$cp_{air}$ ( $kJ/kg K$ )	1.0035
$P_{water}$ ( $kg/m^3$ )	1000
$cp_{water}$ ( $kJ/kg K$ )	4.18
$Q_{human}$ (W)	115

444

Table 1: Parameters with constant value used in this model

445

446 It is noted that this software tool is for academic use. It is not developed in an integrated  
447 software platform, therefore the DM must have basic skills of Excel and Matlab. A flowchart  
448 for the operation of software tool (which is similar in both the case of a new building and an  
449 existing one) is presented in Figure 1.

450

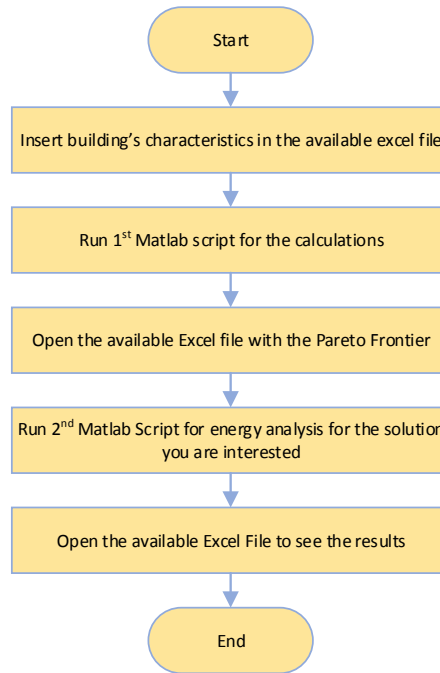


Figure 1: Flowchart for the use of software tool

451

452

## 453 6 Case Study

454

455 In order to evaluate the efficiency and the robustness of the proposed methodology and  
456 software tools, two simulations on a typical detached UK house (see Figure 2) have been  
457 carried out. The building's characteristics are presented in Table 2. The proposed energy  
458 efficient components are presented in Appendix "B" in Table B.1 up to Table B.18. It is noted  
459 that the tables with the proposed components consist also of the data for the existing  
460 components of the building, which would be examined in the next section. The values  
461 regarding the materials, their efficiency and their corresponding cost are from several sources  
462 [5], [16], [27] and from an unofficial internet survey of several UK online retailers.

463

464 The building will be considered both as a new building and as an existing building under  
465 retrofit actions. Moreover, for purposes of comparison the examined building will be placed  
466 and simulated in two different locations where the climate characteristics are very different:  
467 (a) Edinburgh in the UK and (b) Athens in Greece. The climate characteristics of Edinburgh  
468 and Athens are presented in the Table 3. Also, the variables that the DM has to define and are  
469 used for this analysis are presented in Table 4. Moreover, for reasons of simplicity it is  
470 assumed that all the temperature correction factors and shading factors are considered to be  
471 equal to 1. It is further assumed that the cost of the components is the same in both cities and  
472 it will be expressed in Great British Pounds sterling (£).

473



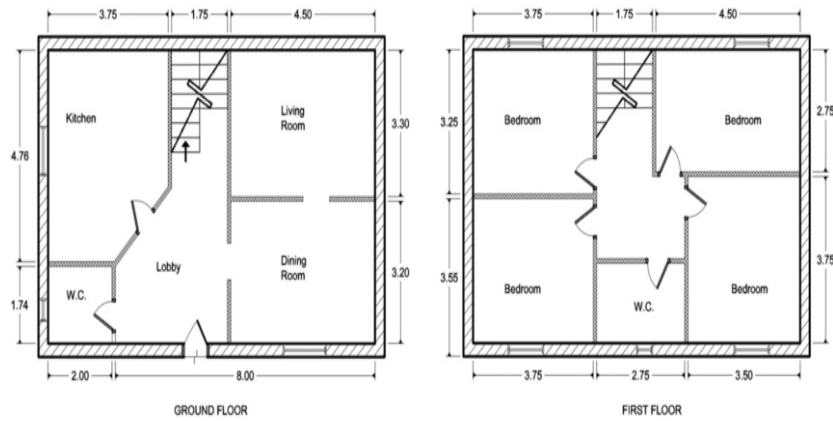


Figure 2: A typical detached house in the UK (source: [35])

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 476

Component	Value
External Wall (m <sup>2</sup> )	194
Internal Wall (m <sup>2</sup> )	99
First floor & ground floor ceiling(m <sup>2</sup> )	62
Ground floor (m <sup>2</sup> )	65
Roof (m <sup>2</sup> )	75
First floor ceiling (m <sup>2</sup> )	65
Windows (m <sup>2</sup> )	13
External doors (m <sup>2</sup> )	3
Internal Volume V (m <sup>3</sup> ) <sup>a</sup>	344

Table 2: Characteristics of the examined building (source: [35])

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 478  
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 481

Note:

<sup>a</sup>: it can be calculated from the building's characteristics after calculating the total volume and subtracting the volume occupied by interior walls

	Air Temperature (°C)		Daily Solar Radiation (kwh/m <sup>2</sup> /day)		Water Temperature (°C)		Relative Humidity (%)	
	EDI <sup>a</sup>	ATH <sup>a</sup>	EDI <sup>a,b</sup>	ATH <sup>a,b</sup>	EDI <sup>c</sup>	ATH <sup>d</sup>	EDI <sup>a</sup>	ATH <sup>a</sup>
<b>January</b>	3.9	7.4	0.57	1.39	9	11.3	83.6%	69.5%
<b>February</b>	4.2	7.8	1.28	1.91	9	10.9	80.5%	64.4%
<b>March</b>	5.6	10.8	2.19	2.78	10	11.8	78.2%	56.7%
<b>April</b>	7.3	15.8	3.32	3.85	13	14.3	77.0%	47.4%
<b>May</b>	10.1	21.5	4.58	5.01	14	17.7	77.0%	39.9%
<b>June</b>	12.9	26.4	4.56	5.27	16	21.6	77.2%	34.5%
<b>July</b>	14.9	28.6	4.31	4.93	18	24.7	78.9%	33.9%
<b>August</b>	14.7	28.0	3.68	4.62	17	25.4	79.1%	36.5%
<b>September</b>	12.5	24.2	2.54	3.93	16	24.2	80.7%	41.6%
<b>October</b>	9.5	18.9	1.45	2.49	15	21.1	82.6%	51.5%
<b>November</b>	6.4	13.1	0.74	1.54	13	16.9	83.7%	63.7%
<b>December</b>	4.5	8.7	0.44	1.22	12	13.5	85.0%	71.2%

Table 3: Climate Characteristics of Edinburgh (EDI) and Athens (ATH)

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 485  
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 488

Notes:

<sup>a</sup>: source [36]

<sup>b</sup>: Daily solar radiation is assumed to be falling at the optimal angle of the area and is calculated with the methodology described in [37]

<sup>c</sup>: source [38]

<sup>d</sup>: source [39]

489

Parameter	Value		Parameter	Value	
	EDI	ATH		EDI	ATH
$T_{IH}$ (°C)	18 [32]	18 [39]	Number of People	4	4
$T_{IC}$ (°C)	24 [32]	26 [39]	$\dot{m}_w$ (l/day)	60 [5]	60 [5]
$T_{DHW}$ (°C)	60 [32]	60 [32]	$n_{grid}$ (%)	35 [16]	35 [16]
$h_i$ (W/m <sup>2</sup> K)	8.3 [27]	8.3 [27]			
$h_o$ (W/m <sup>2</sup> K)	28 [27]	28 [27]			

Table 4: Parameters used in the case studies that are set by the DM

490  
491

## 492 7 Results

493

### 494 7.1 The Case of a New Building

495

496 The obtained results from the simulations are presented in Table 5. The values of the decision  
 497 variables for each working pair of weight coefficients can be seen analytically in Appendix  
 498 “C” from Table C.1 up to Table C.4. It is noted that the software tool took 4 and 4.1 minutes  
 499 in a ‘Windows 8.1’ operating system, supported by a 3.07GHz i7 processor and 12GB RAM,  
 500 to run the simulations for the case of Edinburgh and Athens respectively. This time includes  
 501 the input of the necessary data, all the optimizations and the exportation of the results to the  
 502 Excel spreadsheet file; hence it can be seen that the proposed method and software tool can be  
 503 time efficient.

504

min[u(g <sub>1</sub> (x),g <sub>2</sub> (x))]		P <sub>1</sub>	P <sub>2</sub>	Primary Energy Consumption (MJ/year)		Initial Investment Cost (£)	
EDI	ATH			EDI	ATH	EDI	ATH
0.000	0.000	1.00	0.00	58,499	59,147	53,006	52,031
0.028	0.019	0.95	0.05	58,684	59,274	41,260	40,485
0.054	0.042	0.90	0.10	58,684	59,526	41,260	38,815
0.079	0.064	0.85	0.15	58,857	59,526	40,860	38,815
0.104	0.084	0.80	0.20	59,382	59,976	40,042	37,797
0.119	0.103	0.75	0.25	63,705	59,976	34,642	37,797
0.128	0.123	0.70	0.30	63,705	59,976	34,642	37,797
0.137	0.142	0.65	0.35	63,705	60,199	34,642	37,597
0.145	0.161	0.60	0.40	63,705	60,199	34,642	37,597
0.154	0.159	0.55	0.45	63,705	65,542	34,642	33,867
0.163	0.166	0.50	0.50	63,778	65,542	34,613	33,867
0.171	0.166	0.45	0.55	63,778	69,768	34,613	32,197
0.180	0.165	0.40	0.60	63,778	70,003	34,613	32,126
0.184	0.164	0.35	0.65	68,799	70,342	33,483	32,071
0.178	0.162	0.30	0.70	85,765	70,342	30,562	32,071
0.162	0.148	0.25	0.75	85,765	79,158	30,562	30,469
0.135	0.126	0.20	0.80	99,117	90,519	29,020	29,020
0.106	0.100	0.15	0.85	102,030	90,519	28,809	29,020

$\min[u(g_1(x),g_2(x))]$		$P_1$	$P_2$	Primary Energy Consumption (MJ/year)		Initial Investment Cost (£)	
EDI	ATH			EDI	ATH	EDI	ATH
0.075	0.072	0.10	0.90	102,030	93,926	28,809	28,809
0.043	0.042	0.05	0.95	102,030	93,926	28,809	28,809
0.000	0.000	0.00	1.00	126,899	116,093	28,509	28,509

Table 5: Values of the primary energy consumption and initial investment cost for each working pair using for the case of a new building in Edinburgh (EDI) and Athens (ATH)

505  
506  
507

508 From Table C.1 up to Table C.4 it can be seen that when the primary energy consumption  
 509 criterion is independently minimized the components which have the best energy behaviour  
 510 are selected. This means the components of the building's envelope (doors, windows, wall  
 511 structure, floors structure and ceilings structure) with the lowest  $U_{value}$  are selected, and the  
 512 energy systems with the higher generation efficiency. For instance, it can be seen that the  
 513 Door 2 has been selected, the window type 2 which is a low-e window and so forth. However,  
 514 it is observed that there are differences at each city. In Athens the window 3 that has lower  
 515 SHGC is selected for all the working pairs of weight coefficients. This happens as in Athens  
 516 the solar radiation is higher than in Edinburgh which causes a significant increase in cooling  
 517 demand. By contrast, in Edinburgh the window with the lowest  $U_{value}$  is most frequently  
 518 selected (when the primary energy consumption criterion is more important) in order to  
 519 minimize heating demand.

520

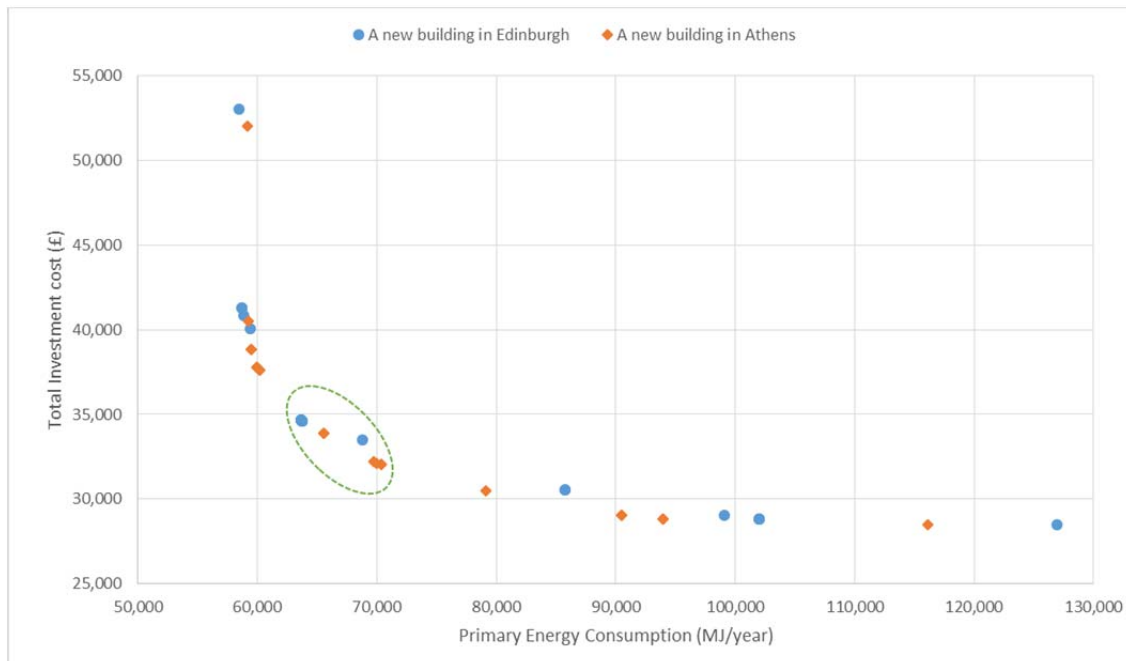
521 In the category of the building's energy systems, in both cities the heating-DHW system 3 is  
 522 selected which is a highly efficient heat pump with a COP 4 and the electrical cooling system  
 523 3 that has is an air-condition system with a COP 3. Also, the LED proposed lamps are chosen  
 524 to provide lighting as they have the lowest power. The same applies for all the electrical  
 525 appliances. In both cities solar collector 1 and photovoltaics 3 have been chosen as they can  
 526 produce more hot water and electricity respectively.

527

528 On the other hand, when the cost criterion is minimized independently, the components with  
 529 the lowest investment cost are selected. As shown in Table 5 the solution is the same for both  
 530 cities. The building's envelopes components with the highest  $U_{value}$  and the energy systems  
 531 with the lowest efficiency are selected. A low efficiency heating-cooling system has been  
 532 selected and a low efficiency oil-based boiler to provide hot water. In addition, a fluorescent  
 533 lamp and electrical appliances with the lowest cost that have the highest power have been  
 534 selected.

535

536 The Pareto frontier that includes the values of primary energy consumption and total  
537 investment cost for all the working weighting pairs is shown in Figure 3 and it represents all  
538 the optimal solutions. It can be seen clearly that the initial investment cost and primary energy  
539 consumption of a building are inversely proportional. The higher the total investment cost, the  
540 lower the primary energy consumption. When the primary energy consumption criterion is  
541 more important the components with the best energy behaviour are selected, but as the cost  
542 criterion gets more important cheaper components are selected, which confirms the general  
543 hypothesis and shows that the methodology and the developed software are robust. It is  
544 suggested that the most preferred solutions for the DM are those indicated in the diagram of  
545 the Pareto frontier, because for these cases a small reduction of the investment cost does not  
546 increase primary energy consumption dramatically.  
547



548

549 *Figure 3: The Pareto Frontier using the weighted sum method for the case study of a new building in*  
550 *the cities of Edinburgh and Athens.*

551

552 The minimal and maximum total initial investment cost comes to £28,509 and £53,006  
553 respectively in Edinburgh and £28,509 and £52,031 respectively in Athens. The minimal and  
554 the maximum primary energy consumption in Edinburgh is 58,499 MJ/year and 126,899  
555 MJ/year respectively; while the minimal and the maximum primary energy consumption in  
556 Athens is 59,147 MJ/year and 116,093 MJ/year respectively. Furthermore, it can be noticed  
557 that the primary energy consumption in Athens and Edinburgh is similar although the climate  
558 characteristics are different, however there are major differences between the energy  
559 categories.

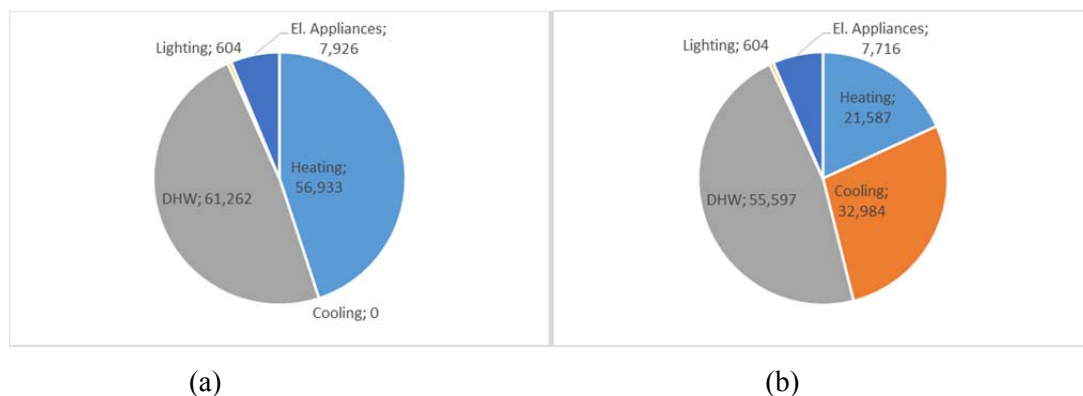
560

561 The importance of the climate characteristics can be seen in more detail by comparing the  
562 energy demand and primary energy consumption of the building in each city. In Figure 4 the  
563 contribution of each energy category to the total annual energy demand is presented for the  
564 case of weight coefficients  $(p_1, p_2)=(0.35, 0.65)$ . As previously mentioned, the DM can use  
565 the software tool to obtain the energy demand and energy consumption analytically for any  
566 working pair of weight coefficients, according to his own preferences. In this analysis, the  
567 particular working pair of weight coefficients has been chosen because is in the area of the  
568 most preferred optimal solutions.

569

570 It is shown that if the building is located in Edinburgh the heating energy demand is the  
571 dominant category, whilst when the building is located in Athens the cooling energy demand  
572 is higher because of the difference in Degree-days in the two cities. In Figure 5 the primary  
573 energy consumption share of each category is presented. It is observed that in Edinburgh the  
574 primary energy consumption for heating has the highest contribution to the total primary  
575 energy, whilst in Athens the primary consumption for the electrical appliances is the highest.  
576 The importance of the chosen components is significant as they can have a major impact on  
577 primary energy consumption. For instance, although in Athens the DHW demand is lower  
578 than in Edinburgh the primary consumption is higher due to the choice of a less efficient  
579 component for the hot water.

580



581

582

583 *Figure 4: Annual Energy Demand (MJ/year) for the case of a new building (a) Edinburgh and (b)*  
584 *Athens, for the case of weight coefficients  $(p_1, p_2)=(0.35, 0.65)$ .*

585

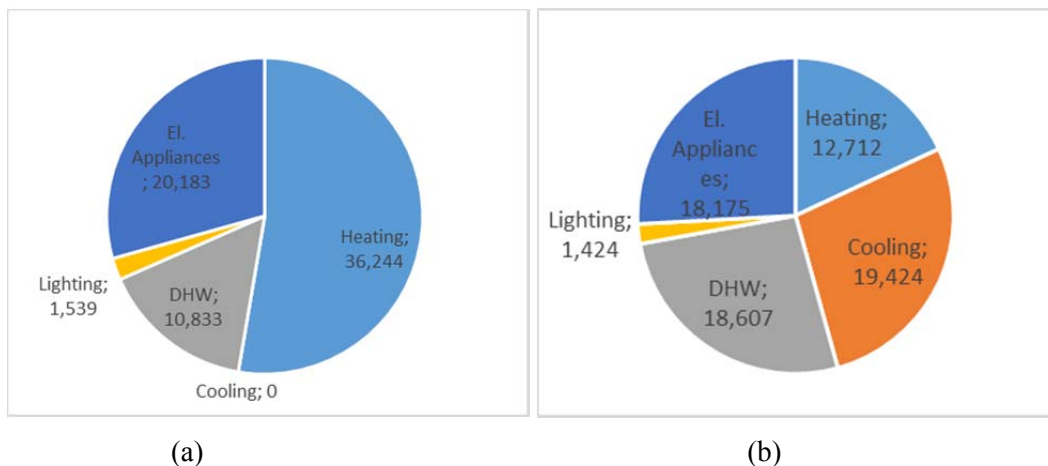


Figure 5: Annual Primary Energy Consumption (MJ/year) for the case of a new building in (a) Edinburgh and (b) Athens, for the case of weight coefficients  $(p_1, p_2) = (0.35, 0.65)$ .

Moreover, solar photovoltaics are chosen for both cities for this case. Electricity generation from RES is important as it can reduce the primary energy consumption significantly. The annual generation from PV in Athens is some 3,856 MJ/year while in Edinburgh is only 2,938 MJ/year which shows that Athens has much higher potential for utilizing solar energy.

## 7.2 The Case of Retrofitting an Existing Building

In this case, the examined building that has been used in the previous section is assumed to be an old existing building in the broader area of Edinburgh and Athens respectively. As mentioned before, the proposed components for each category and the components of the existing buildings are presented from Table B.1 up to Table B.18. It is noted that the existing building has low energy efficient components and is uninsulated.

Using the developed software tool for the case of retrofitting an existing building, the primary energy consumption of the existing building has first been calculated. The total annual primary energy consumption savings for the existing building when is located in Edinburgh and Athens is calculated to be 600,369 MJ/year and 290,801 MJ/year respectively.

The obtained results from the simulations are presented in Table 6. The values of the decision variables for each working pair calculated after the optimizations can be seen analytically in Appendix “C” in the Table C.5 up to the Table C.8. It is noted that the software tool took 4.9 and 4.2 minutes to run the simulations for the case of Edinburgh and Athens respectively. For comparison purposes with the case of a new building in Table 6 is also presented the primary energy consumption after the retrofit actions for the building placed in the city of Edinburgh and Athens respectively.

616

$\min[u(g_1(x),g_2(x))]$		P <sub>1</sub>	P <sub>2</sub>	Primary Energy Consumption Savings (MJ/year)		Primary Energy Consumption (MJ/year)		Initial Investment Cost (£)	
EDI	ATH			EDI	ATH	EDI	ATH	EDI	ATH
0.000	0.000	1.00	0.00	540,687	229,875	59,682	60,927	19,085	18,310
0.029	0.039	0.95	0.05	535,593	229,091	64,776	61,710	12,438	15,422
0.040	0.053	0.90	0.10	513,246	219,281	87,123	71,521	8,347	9,951
0.041	0.067	0.85	0.15	497,410	218,942	102,959	71,859	6,735	9,896
0.040	0.072	0.80	0.20	495,933	197,873	104,436	92,928	6,635	6,886
0.039	0.070	0.75	0.25	495,933	197,528	104,436	93,274	6,635	6,846
0.038	0.068	0.70	0.30	495,933	196,830	104,436	93,972	6,635	6,796
0.037	0.066	0.65	0.35	495,933	194,121	104,436	96,680	6,635	6,635
0.036	0.063	0.60	0.40	495,933	194,121	104,436	96,680	6,635	6,635
0.035	0.060	0.55	0.45	495,933	194,121	104,436	96,680	6,635	6,635
0.033	0.056	0.50	0.50	488,830	194,121	111,539	96,680	6,535	6,635
0.031	0.053	0.45	0.55	480,872	194,121	119,497	96,680	6,435	6,635
0.028	0.050	0.40	0.60	470,262	194,121	130,107	96,680	6,335	6,635
0.024	0.047	0.35	0.65	470,262	194,121	130,107	96,680	6,335	6,635
0.021	0.042	0.30	0.70	470,262	180,550	130,107	110,251	6,335	6,435
0.017	0.036	0.25	0.75	470,262	171,035	130,107	119,766	6,335	6,335
0.014	0.029	0.20	0.80	470,262	171,035	130,107	119,766	6,335	6,335
0.010	0.022	0.15	0.85	470,262	171,035	130,107	119,766	6,335	6,335
0.007	0.015	0.10	0.90	470,262	171,035	130,107	119,766	6,335	6,335
0.003	0.007	0.05	0.95	470,262	171,035	130,107	119,766	6,335	6,335
0.000	0.000	0.00	1.00	470,262	171,035	130,107	119,766	6,335	6,335

617 *Table 6: Values of the primary energy consumption savings and the initial investment cost for each*  
 618 *working pair of weight coefficients for the case of retrofitting an existing building in Edinburgh (EDI)*  
 619 *and Athens (ATH)*  
 620

621 From Table C.5 up to the Table C.8 it is shown that when the primary energy consumption  
 622 criterion is independently minimized the components with the best energy behaviour are  
 623 selected, which is similar to the analysis presented in the previous chapter. In this case the  
 624 initial investment cost is lower as the wall structure, floor structure and ceiling structure are  
 625 not included in the retrofit actions. It is noted that the differences between Edinburgh and  
 626 Athens that existed in the previous chapter still apply. For instance, when the energy criterion  
 627 is independently minimized the components of the building envelope with the lowest  $U_{value}$   
 628 e.g. in Edinburgh the door number 2, window number 2, insulation material number 1 and so  
 629 forth are selected, whilst in Athens window number 3 is again selected in all cases. The same  
 630 energy systems as in the case of a new building have also been selected.

631  
 632 On the other hand, when the cost criterion is minimized independently, the components with  
 633 the lowest initial investment cost are selected (e.g. door number 1, insulation number 3 etc.),  
 634 and the energy systems that were chosen in the case of the new building, which are the same  
 635 for both cities. Solar photovoltaics and solar collector systems are not selected for this case. It  
 636 is observed that when the primary energy consumption savings criterion is more important the  
 637 components with the best energy behaviour are selected, but as the cost criterion gets more

638 important the cheaper components are selected, which confirms the general hypothesis and  
639 showing that the methodology and the developed software is robust. This means that the more  
640 you invest in energy efficient measures the higher the energy savings are and the lower the  
641 primary energy consumption becomes, which is similar to the case of a new building  
642 presented in the previous section.

643

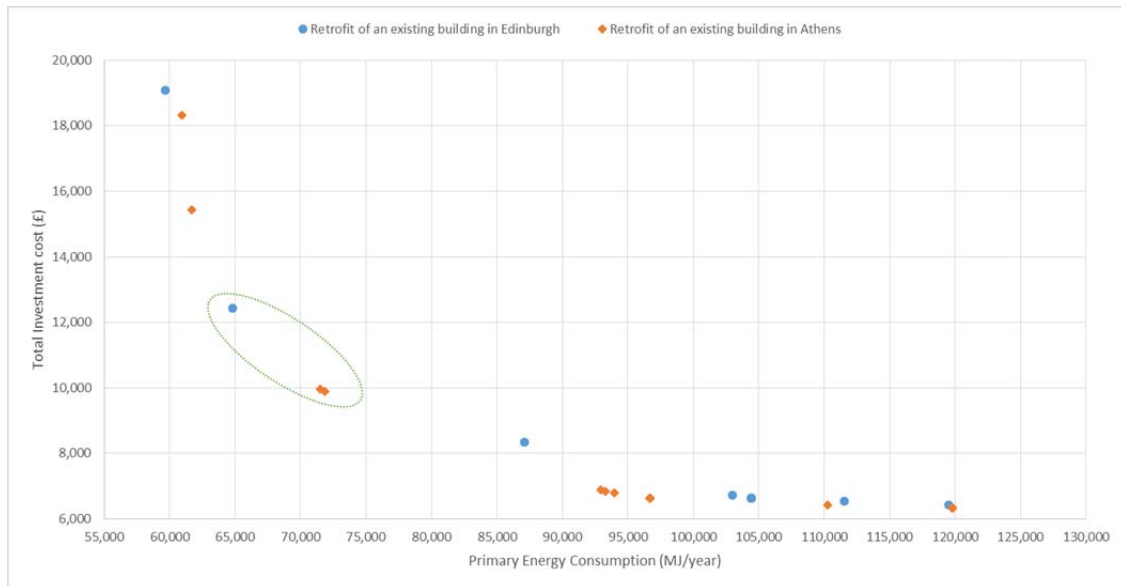
644 The minimal and the maximum total initial investment cost of the components is £6,335 and  
645 £19,085 respectively in Edinburgh and £6,335 and £18,310 respectively in Athens. The  
646 minimal and the maximum primary energy consumption savings in Edinburgh are 470,262  
647 MJ/year (78%) and 540,687 MJ/year (90%) respectively which means that the primary energy  
648 consumption is between 59,682 MJ/year to 130,107 MJ/year. In Athens the minimal and the  
649 maximum primary energy consumption savings are 171,035 MJ/year (59%) and 229,875  
650 MJ/year (79%) respectively, resulting in primary energy consumption between 60,927  
651 MJ/year to 119,766 MJ/year. In the case of retrofitting an existing building the initial  
652 investment cost is lower than the case of the new building presented in the previous chapter  
653 because the wall structure, floor structure and ceiling structure are not included in the retrofit  
654 actions.

655

656 The results for the other weight coefficients working pairs are in-between those values. The  
657 Pareto frontier diagram shown in Figure 6 for the case of the retrofitting an existing building  
658 in Edinburgh and Athens respectively represents all the optimal solutions. It can be indicated  
659 that also in this case the initial investment cost and primary energy consumption of a building  
660 are inversely proportional.

661





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*Figure 6: The Pareto Frontier using the weighted sum method for the case study of retrofitting an existing building in Edinburgh*

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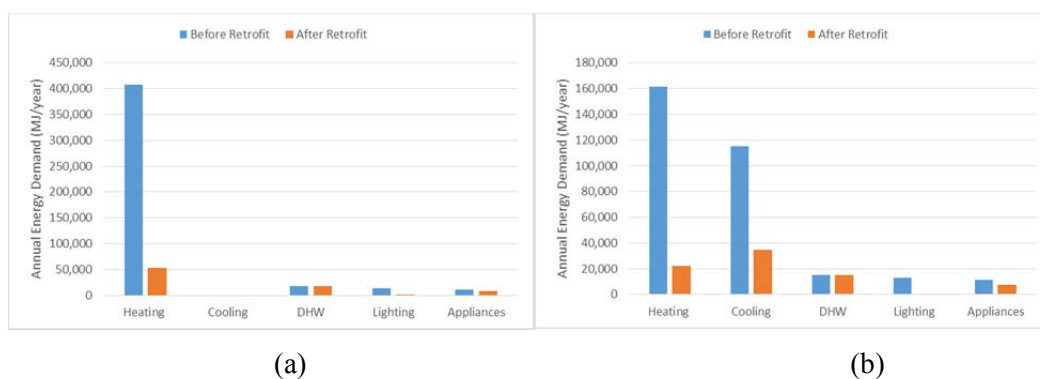
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676

The possibility of primary energy consumption savings is high in both cities but is greater in Edinburgh than in Athens due to the differences in climate characteristics. This is indicated with further analysis of the energy demand and of the primary energy consumption of each category. Figure 7 and Figure 8 present the energy demand and the primary energy consumption of the existing building before and after the retrofit actions in Edinburgh and Athens for the case of working weight coefficients  $(p_1, p_2)=(0.95, 0.05)$  and  $(p_1, p_2)=(0.85, 0.15)$  respectively. Those working pairs have been chosen as they belong in the area with the most preferred optimal solutions. It can be seen that when the best energy efficient measures are selected the energy demand is reduced significantly, resulting in high primary energy savings.

677

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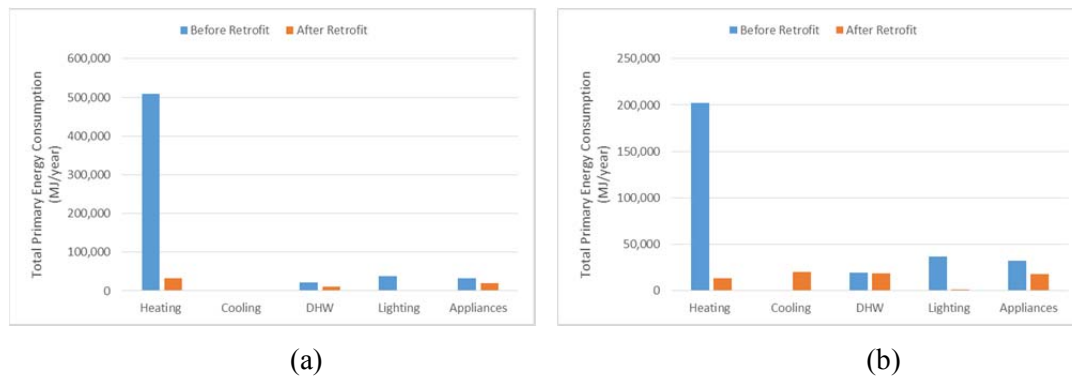


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*Figure 7: Annual Energy Demand before and after the retrofit for an existing building in (a) Edinburgh and (b) Athens, for the case of working weight coefficient  $(p_1, p_2)=(0.55, 0.45)$*



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687

Figure 8: Annual primary energy consumption before and after the retrofit for an existing building in (a) Edinburgh and (b) Athens, for the case of working weight coefficient  $(p_1, p_2) = (0.55, 0.45)$  and  $(p_1, p_2) = (0.65, 0.35)$  for Edinburgh and Athens respectively

## 688 8 Conclusions

689

### 690 8.1 Main Findings

691

692 The minimization of energy demand and primary energy consumption in the building sector is  
693 essential in order to reduce the energy consumption in the overall energy supply chain and  
694 lead to sustainability in buildings. The reduction of primary energy in buildings will also  
695 contribute in the achievement of the policy goals set by the UK Government and the  
696 European Commission by the EPBD. Moreover, if less primary energy is used from fossil  
697 fuels then the carbon dioxide emissions would also get reduced.

698

699 The scope of the present article is to expand a previously developed methodology to  
700 optimally prioritize energy efficiency measures in terms of their energy behaviour and the  
701 initial cost and also develop a software tool to be used by a DM. The methodology is generic  
702 and can be used in order to optimally prioritize the energy efficiency measures for the case of  
703 a new building and for the case of retrofitting an existing one. As described in Section 3, the  
704 proposed methodology is depended on previous work with a more limited number of energy  
705 efficiency measures and it was further expanded to take into account more categories of  
706 energy efficiency measures, and also to analyse the case of retrofitting an existing building.  
707 Many criteria exist to assess the energy efficiency measures but in the current article only the  
708 primary energy consumption and the initial investment cost have been used, resulting in a  
709 multi-objective optimisation problem.

710

711 Moreover, two software tools have been developed to allow the DM to propose energy  
712 efficiency measures and prioritize them according to his own preferences, in the case of a new  
713 building and of retrofitting an existing one. In order to solve the MINLP multi-objective

714 problem the weighted sum method has been used and the ‘bonmin’ algorithm has been  
715 chosen. The software tools have been examined in two case studies, each for a new and  
716 existing building, and they have been proven to be robust and time efficient. The analysis  
717 showed that the more someone invests in energy efficiency the lower the primary energy  
718 consumption becomes. Hence, a DM according to his own preferences can find the most  
719 preferable solution from the provided Pareto front.

720

## 721 **8.2 Proposals for Future Work**

722

723 As previously mentioned, the two decision criteria used in this methodology are the primary  
724 energy consumption and the initial investment cost. However, there are also many other  
725 criteria that refer to energy efficiency measures (e.g. life cycle cost or operating cost). A DM  
726 would probably be more interested in reducing the operating costs and his bills. Moreover,  
727 environmental criteria could be also used such as the carbon dioxide emissions. As the  
728 climate is one of the major challenges the planet faces a software tool that takes into account  
729 the life cycle cost of the components and the carbon dioxide emissions or the global warming  
730 potential might be preferable. It must be noted that our software tool could be expanded to  
731 being capable of dealing with more than two objective functions (criteria).

732

733 Another constraint of the developed methodology is that it assumes that the loads are  
734 constant, i.e. it is a steady-state approach. A methodology that would examine the energy  
735 demand variations on a time basis would provide more accurate results but it would be more  
736 difficult to solve. Also, the software tool can be further expanded to include wind energy or  
737 CHP units and more categories of electrical appliances. Moreover, the software tool can be  
738 further developed and become a software package in a more compact form that could be  
739 executed independently without the need of a DM having ‘Matlab<sup>®</sup>’ installed.

740

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742

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- 839

## Nomenclature

Symbol	Description	Unit
ACH	Air changes per hour	$\text{h}^{-1}$
ASLC	Area of a solar collector	$\text{m}^2$
$A_{\text{win}}$	Area of a window	$\text{m}^2$
BLC	Building load factor	W/K
COSTCEIL	Initial investment cost for ceilings	£
COSTCS	Initial investment cost for a cooling system	£
COSTDOR	Initial investment cost for doors	£
COSTEA	Initial investment cost for electrical appliances	£
COSTFLO	Initial investment cost for floors	£
COSTHCS	Initial investment cost for a heating-cooling system	£
COSTHS	Initial investment cost for a heating system	£
COSTHWS	Initial investment cost for a heating-DHW system	£
COSTLIGHT	Initial investment cost for lamps	£
COSTRES	Initial investment cost for a RES power system	£
COSTSLC	Initial investment cost for a solar collector	£
COSTWAL	Initial investment cost for walls	£
COSTWIN	Initial investment cost for windows	£
$c_{p,\text{air}}$	Specific heat of air at constant pressure	$\text{kJ/kg/K}$
$c_{p,\text{wat}}$	Specific heat of water at constant pressure	$\text{kJ/kg/K}$
$CS_m$	Indicator for cooling demand each month	-
$F_{c,m,wn}$	Window correction factor for movable devices	%
$F_{F,wn}$	Frame factor of a window	%
$f_{\text{grid}}$	Percentage of electricity supply from the grid	%
$F_s$	shading factor of a solar collector	%
$F_{s,wn}$	Shading factor of a window	%
$f_{\text{use}}$	Factor indicating the usage of a device each day	h/day
$h$	Heat transfer convection coefficient	$\text{W/m}^2\text{K}$
$h_i$	indoors combined convection-radiation coefficient	$\text{W/m}^2\text{K}$
$h_o$	outdoors combined convection-radiation coefficient	$\text{W/m}^2\text{K}$
$HS_m$	Indicator for heating demand each month	-
$I_{\text{SL}}$	Solar radiation	$\text{kWh/m}^2/\text{day}$

Symbol	Description	Unit
$k$	Thermal conductivity	W/mK
$l$	Thickness of a material	M
$\dot{m}_w$	Daily need of hot water	L/day
$n_{ecsi,ecsj}^{ECS}$	Efficiency of an electric system $ecsj$ of category $ecsi$	%
$n_{ehsi,ehsj}^{EHS}$	Efficiency of an electric system $ehsj$ of category $ehsi$ for heating	%
$n_{ehcsi,ehcsj}^{EHCS}$	Efficiency of an electric system $ehcsj$ of category $ehcsi$ for heating-cooling	%
$n_{ehwsi,ehwsj}^{EHWS}$	Efficiency of an electric system $ehwj$ of category $ehwi$ used for heating- DHW	%
$n_{ewsi,ewsj}^{EWS}$	Efficiency of an electrical system $ewj$ of category $ewi$ for DHW	%
$n_{grid}$	Average efficiency of power generation of the grid	%
$n_{nehsi,nehsj}^{NEHS}$	Efficiency of a non-electric system $nehsj$ of category $nehsi$ used for heating	%
$n_{nehwsi,ehwsj}^{NEHWS}$	Efficiency of a non-electric system $nehwsj$ of category $nehwsi$ used for heating-DHW	%
$n_{newsi,ewsj}^{NEWS}$	Efficiency of a non-electric system $newsj$ of category $newsi$ used for DHW	%
$n_{slci,slcj}^{SLC}$	Efficiency of a non-electric system $nehwsj$ of category $nehwsi$ used for heating-DHW	%
$n_{tot}$	Total efficiency of a CHP unit	%
$P_L$	Power Rate of a Lamp	W
$q''$	Heat Flux	W/m <sup>2</sup>
$Q_C$	Annual primary energy consumption for cooling	MJ/year
$Q^{CD}$	Annual cooling demand	MJ/year
$Q_{el}^C$	Annual primary energy consumption for cooling consumed by an electrical system	MJ/year
$Q_{DHW}$	Annual primary energy consumption for DHW	MJ/year
$Q_{dSLC,m}$	Energy provided by a solar collector for DHW	MJ/month
$Q_{ea}$	Heat emitted from appliances	W
$Q^H$	Annual primary energy consumption for heating	MJ/year
$Q_{nel,fuel}^H$	Annual primary energy consumption for heating from a non-electrical system using a specific fuel	MJ/year



Symbol	Description	Unit
$Q_{el}^H$	Annual primary energy consumption for heating from an electrical system	MJ/year
$Q^{HD}$	Annual heating energy demand	MJ/year
$Q_{human}$	Heat emitted from people	W
$Q_{INH,G,m}$	Internal heat gain each month	kWh/month
$Q_{lamp}$	electricity consumption of a lamp	kWh/day
$Q_L$	Annual primary energy consumption for lighting	MJ/year
$Q^{LD}$	Annual energy demand for lighting	MJ/year
$Q_{SL,m}$	Solar heat gain each month	kWh/month
$Q_{T,m}$	Heat transmission losses each month	kWh/month
$Q_{ven,m}$	Ventilation losses each month	kWh/month
$Q_{el}^W$	Annual primary energy consumption of an electrical system for DHW	MJ/year
$Q_{nel,fuel}^W$	Annual primary energy consumption for DHW by a non-electrical system	MJ/year
$Q^{WD}$	Annual energy demand for DHW	MJ/year
$T$	Temperature	°C
$t_d$	Duration of a month in days	days/month
$T_{DCW}$	Temperature of cold water inlet to the DHW system	°C
$T_{DHW}$	Supply temperature of hot water by the DHW system	°C
$T_{IH}$	Internal design temperature for heating season	°C
$t_L$	Operation time of a lamp	h/day
$t_m$	Month duration in hours	h/month
$T_{o,m}$	Average air temperature of each month	°C
$U$	Overall heat transfer coefficient	W/m <sup>2</sup> K
$V$	Internal volume of the building	m <sup>3</sup>
$WS_m$	Indicator for DHW demand each month	binary
$x_d^{DOOR}$	Decision variable for doors	binary
$x_{eai,eaj}^{EA}$	Decision variable of electric appliance $eaj$ of category $eai$	binary
$x_{ecsi,ecsj}^{ECS}$	Decision variable for an electrical cooling system $ecsj$ of categories $ecsi$	binary
$x_{ehsi,ehsj}^{EHS}$	Decision variable for an electrical heating system $ehsj$ of categories $ehsi$	binary
$x_{ehcsi,ehcsj}^{EHCS}$	Decision variable for an electrical heating-cooling system	binary

Symbol	Description	Unit
	<i>ehcsj</i> of category <i>ehcsi</i>	
$x_{ehwsi,ehwsj}^{EHWS}$	Decision variable for an electrical heating-DHW system <i>ehwsj</i> of category <i>ehwsi</i>	binary
$x_h^{FLO}$	Decision variable for floor structure <i>h</i>	binary
$x_{li,lj}^L$	Decision variable of lamp <i>lj</i> of category <i>li</i>	binary
$x_{nehsti,nehstj}^{NEHS}$	Decision variable for a non-electrical heating system <i>nehstj</i> of categories <i>nehsti</i>	binary
$x_{nehwsi,nehwsj}^{NEHWS}$	Decision variable for a non-electrical heating-DHW system <i>nehwsj</i> of category <i>nehwsi</i>	binary
$x_r^{CEIL}$	Decision variable for ceiling structure <i>r</i>	binary
$x_{resi,resj}^{RES}$	Decision variable for a RES energy system <i>resj</i> of category <i>resi</i>	binary
$x_{slci,slcj}^{SLC}$	Decision variable for a solar collector system <i>slcj</i> of category <i>slci</i>	binary
$x_{zt}^{WIN}$	Decision variable for windows type <i>z</i>	binary
$x_w^{WALL}$	Decision variable for wall structure <i>w</i>	binary
$\rho_{air}$	Air density	kg/m <sup>3</sup>
$\rho_{wat}$	Water density	kg/m <sup>3</sup>

## Appendix “A”: Equations of the model

### A.1 Decision Variables

#### A.1.1 Building Envelope

##### a. Doors

Let  $D$  be the available number of alternative type of doors. A decision variable  $x_d^{DOOR}$  where,  $d = 1, \dots, D$ , is defined such as:

$$x_d^{DOOR} = \begin{cases} 1, & \text{if door type } d \text{ is selected} \\ 0, & \text{else} \end{cases} \quad (\text{A.1})$$

It is assumed that the available proposed doors are of the same type and only one can be selected, which leads to the following constraint:

$$\sum_{d=1}^D x_d^{DOOR} = 1 \quad (\text{A.2})$$

##### b. Windows

Let  $Z$  be the available number of alternative type of windows (e.g. double glaze, low-e) where each consists of  $T_z$  sub-types (e.g. xenon-filled, vacuum-filled). A decision variable  $x_{zt}^{WIN}$  where  $z = 1, \dots, Z$  and  $t = 1, \dots, T_z$  is defined such as:

$$x_{zt}^{WIN} = \begin{cases} 1, & \text{if window sub-type } t \text{ of type } z \text{ is selected} \\ 0, & \text{else} \end{cases} \quad (\text{A.3})$$

It is assumed that the available window types are of the same type and only one may be selected, which leads to the following constraint:

$$\sum_{z=1}^Z \sum_{t=1}^{T_z} x_{zt}^{WIN} = 1 \quad (\text{A.4})$$

##### c. Walls

Let  $W$  be the available number of alternative types of structures of wall structures. A decision variable  $x_w^{WALL}$  where  $w = 1, \dots, W$  is defined such as:

$$x_w^{WALL} = \begin{cases} 1, & \text{if wall structure } w \text{ is selected} \\ 0, & \text{else} \end{cases} \quad (\text{A.5})$$

It is assumed that from the available wall structures only one may be selected, which leads to the following constraint:

$$\sum_{w=1}^W x_w^{WALL} = 1 \quad (\text{A.6})$$

Furthermore, each wall structure consists of  $NWL_w$  number of known layers (with  $nwl = 1, \dots, NWL_w$ ). The materials of these layers have specific thermal conductivities  $kk_{w,nwl}^{WALL}$  ( $W/m K$ ) and thicknesses  $l_{w,nwl}^{WALL}$  ( $m$ ).

Also let  $Y_w$  (with  $y = 1, \dots, Y_w$ ) be the number of unknown layers (e.g. insulation) layer where their materials have to be chosen between the available ones. For each unknown layer  $y$  of structure  $w$  there are  $P_{wy}$  (with  $p = 1, \dots, P_{wy}$ ) alternative materials available and only one is allowed to be chosen for the respected structure. Therefore, the following decision variable and constraint are defined:

$$x_{wyp}^{mWALL} = \begin{cases} 1, & \text{if material } p \text{ is selected for layer } y \text{ of wall structure } w \\ 0, & \text{else} \end{cases} \quad (\text{A.7})$$

$$\sum_{p=1}^{P_{wy}} x_{wyp}^{mWALL} = x_w^{WALL} \quad \forall (y = 1, \dots, Y_w \quad \forall w = 1, \dots, W) \quad (\text{A.8})$$

The thickness of the unknown layers of materials  $Y_w$  is considered to be predefined. Also, each of material  $c$  of layer  $y$  of wall structure  $w$  has  $kk_{wyc}^{mWALL}$  ( $W/m K$ ) thermal conductivity and  $l_{wyc}^{WALL}$  thickness.

#### d. Ceilings

Similarly to walls, let  $R$  be the number of available alternative structures of ceilings. A binary decision available  $x_r^{CEIL}$  where  $r = 1, \dots, R$  is defined such as:

$$x_r^{CEIL} = \begin{cases} 1, & \text{if ceiling structure } r \text{ is selected} \\ 0, & \text{else} \end{cases} \quad (\text{A.9})$$

Also, it is assumed that only one ceiling structure may be selected from all the proposed ceiling structures, which leads to the following constraint:

$$\sum_{r=1}^R x_r^{CEIL} = 1 \quad (A.10)$$

Also, let  $NCL_r$  be the number of the known layers of the ceiling structure  $r$  with  $ncl = 1, \dots, NCL_r$ ). The materials of these layers have specific thermal conductivities  $kk_{r,ncl}^{LCEIL}$  ( $W/m K$ ) and thicknesses  $l_{r,ncl}^{LCEIL}$  ( $m$ ) which are already known.

Also there is a number  $F_r$  (with  $f = 1, \dots, F_r$ ) of unknown layers where their materials have to be chosen between the available ones. For each unknown layer  $f$  of structure  $r$  there are  $A_{rf}$  (with  $a = 1, \dots, A_{rf}$ ) alternative materials available and one can be selected for the chosen structure. Therefore, the following decision variable and constraint are defined:

$$x_{rfa}^{mCEIL} = \begin{cases} 1, & \text{if material } \alpha \text{ is selected for layer } f \text{ of ceiling structure } r \\ 0, & \text{else} \end{cases} \quad (A.11)$$

$$\sum_{a=1}^{A_{rf}} x_{rfa}^{mCEIL} = x_r^{CEIL} \quad \forall (f = 1, \dots, F_r \quad \forall r = 1, \dots, R) \quad (A.12)$$

The thickness of the unknown layers of materials  $F_r$  is considered to be predefined Also, each of material  $a$  of layer  $f$  of ceiling structure  $r$  has  $k_{rfa}^{mCEIL}$  ( $W/m K$ ) thermal conductivity and  $l_{dfa}^{mCEIL}$  thickness.

#### e. Floors

Similarly to the approach for walls and ceilings, let  $H$  be the number of available alternative structures of floors, which leads to the decision variable  $x_h^{FLO}$  where  $h = 1, \dots, H$  is defined as:

$$x_h^{FLO} = \begin{cases} 1, & \text{if floor structure } h \text{ is selected} \\ 0, & \text{else} \end{cases} \quad (A.13)$$

Also, it is assumed that only one floor structure may be selected from all the proposed floor structures, leading to the following constraint:

$$\sum_{h=1}^H x_h^{FLO} = 1 \quad (\text{A.14})$$

Each floor structure  $h$  consists of  $NFL_h$  layers (with  $nfl = 1, \dots, NFL_h$ ). The materials of these layers have specific thermal conductivities  $kk_{h,nfl}^{FLO}$  ( $W/m K$ ) and thicknesses  $l_{h,nfl}^{FLO}$  ( $m$ ) are already known.

Also there is a number  $E_h$  (with  $e = 1, \dots, E_h$ ) of unknown layers where their materials have to be chosen between the available ones. For each unknown layer  $e$  of structure  $h$  there are  $G_{he}$  alternative materials available and one can be selected for the chosen structure. Therefore, the following decision variable and constraint are defined:

$$x_{heg}^{mFLO} = \begin{cases} 1, & \text{if material } g \text{ is selected for layer } e \text{ of floor structure } h \\ 0, & \text{else} \end{cases} \quad (\text{A.15})$$

$$\sum_{g=1}^{G_{he}} x_{heg}^{mFLO} = x_h^{FLO} \quad \forall (e = 1, \dots, E_h \quad \forall h = 1, \dots, H) \quad (\text{A.16})$$

The thickness of the unknown layers of materials  $E_h$  is considered to be predefined. Also, each of material  $g$  of layer  $e$  of floor structure  $h$  has  $kk_{heg}^{mFLO}$  ( $W/m K$ ) thermal conductivity and  $l_{heg}^{mFLO}$  thickness.

### A.1.2 Building's energy systems

The energy systems categories that are assumed to be available in this methodology are:

- Heating systems: Provide only heating and can be electrical or non-electrical systems which are further categorized according to their input fuel;
- Cooling systems: Provide only cooling (in this approach only electrical systems are assumed to be available)
- DHW systems: Provide only hot water. They can be electrical or non-electrical, which are further categorized according to their input fuel;
- Heating – cooling systems: Provide both space heating and cooling (only electrical systems are assumed to be available);
- Heating – DHW systems: Provide both space heating and DHW supply. They can be electrical or non-electrical which are further categorized according to their input fuel;
- Solar collector systems: Supply DHW by utilizing solar energy;

- Electricity generation systems: Provide electricity using RES.

The decision variables regarding the above systems are defined as follows:

Let  $EHSI$  be the available categories of electrical heating systems which include  $EHSJ_{ehi}$  systems, and let  $NEHSI$  be the available categories of non-electrical heating systems including  $NEHSJ_{nehsi}$  different systems, where  $ehsi = 1, \dots, EHSI$ ,  $ehsj = 1, \dots, EHSJ_{ehsi}$ ,  $nehsi = 1, \dots, NEHSI$ ,  $nehsj = 1, \dots, NEHS_{nehsi}$ . Then the binary decision variables defined are:

$$x_{ehsi, ehsj}^{EHS} = \begin{cases} 1, & \text{if an electrical heating system } ehsj \text{ of category } ehsi \text{ is selected} \\ 0, & \text{else} \end{cases} \quad (\text{A.17})$$

$$x_{nehsi, nehsj}^{NEHS} = \begin{cases} 1, & \text{if a non-electrical heating system } nehsj \text{ of category } nehsi \text{ is selected} \\ 0, & \text{else} \end{cases} \quad (\text{A.18})$$

- Let  $ECSI$  be the available categories of electrical cooling systems which include  $ECSJ_{ecsi}$  systems where  $ecsi = 1, \dots, ECSI$  and  $ecsj = 1, \dots, ECSJ_{ecsi}$ :

$$x_{ecsi, ecsj}^{ECS} = \begin{cases} 1, & \text{if an electrical cooling system } ecsj \text{ of category } ecsi \text{ is selected} \\ 0, & \text{else} \end{cases} \quad (\text{A.19})$$

- Let  $EWSI$  be the available categories of electrical DHW systems categories which includes  $EWSJ_{ewsi}$  systems and the let  $NEWSI$  be the available categories of non-electrical DHW systems consisting of  $NEWSJ_{newsi}$  different systems, where  $ewsi = 1, \dots, EWSI$ ,  $ewsj = 1, \dots, EWSJ_{ewsi}$ ,  $newsi = 1, \dots, NEWSI$  and  $newsj = 1, \dots, NEWSJ_{newsi}$ :

$$x_{ewsi, ewsj}^{EWS} = \begin{cases} 1, & \text{if a DHW system } ewsj \text{ of category } ewsi \text{ is selected} \\ 0, & \text{else} \end{cases} \quad (\text{A.20})$$

$$(\text{A.21})$$

$$x_{newsi, newsj}^{NEWS} = \begin{cases} 1, & \text{if a non-electrical DHW system } newsj \\ \text{of category } newsi \text{ is selected} \\ 0, & \text{else} \end{cases} \quad (\text{A.22})$$

- Let  $EHCSI$  be the available categories of electrical heating - cooling systems consisting of  $EHCSJ_{ehcsi}$  systems, where  $ehcsi = 1, \dots, EHCSI$  and  $ehcsj = 1, \dots, EHCSJ_{ehcsi}$ :

$$x_{ehcsi, ehcsj}^{EHCS} = \begin{cases} 1, & \text{if an electrical heating-cooling system } ehcsj \text{ of category } ehcsi \text{ is selected} \\ 0, & \text{else} \end{cases} \quad (\text{A.23})$$

- Let  $EHWSI$  be the available categories of electrical heating – DHW systems consisting of  $EHWSJ_{ehwsi}$  systems and let  $NEHWSI$  be the available categories of non-electrical heating–DHW systems consisting of  $NEHWSJ_{nehwsi}$  different systems, where  $ehwsi = 1, \dots, EHWSI$ ,  $ehwsj = 1, \dots, EHWSJ_{ehwsi}$ ,  $nehwsi = 1, \dots, NEHWSI$  and  $nehwsj = 1, \dots, NEHWSJ_{nehwsi}$ :

$$x_{ehwsi, ehwsj}^{EHWS} = \begin{cases} 1, & \text{if an electrical heating – DHW system } ehwsj \\ & \text{of category } ehwsi \text{ is selected} \\ 0, & \text{else} \end{cases} \quad (\text{A.24})$$

$$x_{nehwsi, nehwsj}^{NEHWS} = \begin{cases} 1, & \text{if a non-electrical heating – DHW system } \\ & nehwsj \text{ of category } nehwsi \text{ is selected} \\ 0, & \text{else} \end{cases} \quad (\text{A.25})$$

- Let  $SLCI$  be the available categories of solar collector systems consisting of  $SLCJ$  different systems, where  $slci = 1, \dots, SLCI$  and  $slcj = 1, \dots, SLCJ$ :

$$x_{slci, slcj}^{SLC} = \begin{cases} 1, & \text{if solar collector } slcj \text{ of category } slci \text{ is selected} \\ 0, & \text{else} \end{cases} \quad (\text{A.26})$$

- Let  $RESI$  be the available categories of RES electricity generation systems consisting of  $RESJ_{resi}$  different systems, where  $resi = 1, \dots, RESI$  and  $resj = 1, \dots, RESJ_{resi}$ :

$$x_{resi, resj}^{RES} = \begin{cases} 1, & \text{if RES power generation system } \\ & resj \text{ of category } resi \text{ is selected} \\ 0, & \text{else} \end{cases} \quad (\text{A.27})$$

Some of the systems described above could belong into more than one categories. Therefore, some additional constraints are required in order to allow for the selection of only *one* system for each purpose:



- Space heating system amongst those available:

$$\begin{aligned} & \sum_{ehsi=1}^{EHSI} \sum_{ehsj=1}^{EHSJ_{ehi}} x_{ehsi,ehsj}^{EHS} + \sum_{nehsi=1}^{NEHSI} \sum_{nehsj=1}^{NEHSJ_{ehi}} x_{nehsi,nehsj}^{NEHS} + \sum_{ehcsi=1}^{EHCSI} \sum_{ehcsj=1}^{EHCSJ_{ehci}} x_{ehcsi,ehcsj}^{EHCS} \\ & + \sum_{ehwsi=1}^{EHWSI} \sum_{ehwsj=1}^{EHWSJ_{ehwsi}} x_{ehwsi,ehwsj}^{EHWS} + \sum_{nehwsi=1}^{NEHWSI} \sum_{nehwsj=1}^{NEHWSJ_{ehwsi}} x_{nehwsi,nehwsj}^{NEHWS} = 1 \end{aligned} \quad (A.28)$$

- Space cooling system amongst those available:

$$\sum_{ecsi=1}^{ECSI} \sum_{ecsj=1}^{ECJ_{ecsi}} x_{ecsi,ecsj}^{ECS} + \sum_{ehcsi=1}^{EHCSI} \sum_{ehcsj=1}^{EHCSJ_{ehci}} x_{ehcsi,ehcsj}^{EHCS} = 1 \quad (A.29)$$

- DHW system amongst those available:

$$\begin{aligned} & \sum_{ewsi=1}^{EWSI} \sum_{ewsj=1}^{EWSJ_{ewi}} x_{ewsi,ewsj}^{EWS} + \sum_{newsi=1}^{NEWSI} \sum_{newsj=1}^{NEWSJ_{ehsi}} x_{newsi,newsj}^{NEW} + \sum_{ehwsi=1}^{EHWSI} \sum_{ehwsj=1}^{EHWSJ_{ehwsi}} x_{ehwsi,ehwsj}^{EHWS} \\ & + \sum_{nehwsi=1}^{NEHWSI} \sum_{nehwsj=1}^{NEHWSJ_{ehwsi}} x_{nehwsi,nehwsj}^{NEHWS} = 1 \end{aligned} \quad (A.30)$$

- Solar collector system to provide DHW amongst those available if would be beneficial to choose one:

$$\sum_{slci=1}^{SLCI} \sum_{slcj=1}^{SLCJ} x_{slci,slcj}^{SLC} \leq 1 \quad (A.31)$$

- RES electricity system amongst those available if one would be beneficial. It is noted that it is assumed that the building would be connected to the grid:

$$\sum_{resi=1}^{RESI} \sum_{resj=1}^{RESJ_{ehci}} x_{resi,resj}^{RES} \leq 1 \quad (A.32)$$

### A.1.3 Lighting systems

Let  $LI$  be the number of available categories of lighting systems, consisting of  $LJ_{li}$  types of lamps. Then the decision variable  $x_{li,lj}^L$ , where  $li = 1, \dots, LI$  and  $lj = 1, \dots, LJ_{li}$  is defined such as:

$$x_{li,lj}^L = \begin{cases} 1, & \text{if lamp type } lj \text{ of category } li \text{ is selected} \\ 0, & \text{else} \end{cases} \quad (A.33)$$

Assuming that from the available lamps only one can be selected the following constraint is defined:

$$\sum_{li=1}^{LI} \sum_{lj=1}^{LJ_{li}} x_{li, lj}^L = 1 \quad (\text{A.34})$$

#### A.1.4 Electrical appliances

Let  $EAI$  be the number of available categories electrical appliances consisting  $EAJ$  types of appliances available. Then the decision variable  $x_{eai, eaj}^{EA}$ , where  $eai = 1, \dots, EAI$  and  $eaj = 1, \dots, EAJ_{eai}$ , is defined such as :

$$x_{eai, eaj}^{EA} = \begin{cases} 1, & \text{if the electric appliance } eaj \text{ is selected of category } eai \\ 0, & \text{else} \end{cases} \quad (\text{A.35})$$

Assuming that from the available electrical appliances only one can be selected for each category the following constraints are defined:

$$\sum_{eaj=1}^{EAJ_{eai}} x_{eai, eaj}^{EA} = 1 \quad (\text{A.36})$$

$$\sum_{eai=1}^{EAI} \sum_{eaj=1}^{EAJ_{eai}} x_{eai, eaj}^{EA} = EAI, \quad \forall (eaj = 1, \dots, EAJ_{eai} \quad \forall eai = 1, \dots, EAI) \quad (\text{A.37})$$

## A.2 Constraints

### A.2.1 Primary Energy consumption

The total annual primary energy consumption in a building is the primary energy used for heating, cooling, DHW, lighting and electrical appliances [32]:

$$Q_T = Q_H + Q_C + Q_{DHW} + Q_L + Q_A \quad (\text{A.38})$$

#### A.2.1.1 Primary Energy Consumption for Heating

Annually, the total annual primary energy consumption for heating would be equal to:

$$Q_H = \frac{Q_{el}^H f^{grid}}{n_{grid}} + \sum_{fuel=1}^{FUEL} Q_{nel,fuel}^H \quad (A.39)$$

where:

$Q_{el}^H$ : Energy consumed by an electrical system for heating purposes (MJ/year)

$f^{grid}$ : Percentage of electricity supply from the grid (RES electricity supply does not contribute to primary energy consumption).

$n_{el}$ : The average efficiency for the electricity supply from the grid to the building (it is assumed to be 0.35 [16])

$Q_{nel,fuel}^H$ : Energy consumed by a non-electrical system using a  $fuel$  (where  $fuel = 1, \dots, FUEL$ ) (MJ/year)

The energy consumed by an electrical and a non-electrical system can be calculated as:

$$Q_{el}^H = Q^{HD} SEH_{el} \quad (A.40)$$

$$Q_{nel,fuel}^H = Q^{HD} SEH_{nel,fuel} \quad (A.41)$$

where:

$Q^{HD}$ : The total annual heating energy demand (MJ/year)

$$SEH_{el} = \sum_{ehsi=1}^{EHSI} \sum_{ehsj=1}^{EHSJ_{ehsi}} \left( \frac{x_{ehsi,ehsj}^{EHS}}{n_{ehsi,ehsj}^{EHS}} \right) + \sum_{ehcsi=1}^{EHCSI} \sum_{ehcsj=1}^{EHCSJ_{ehcsi}} \left( \frac{x_{ehcsi,ehcsj}^{EHCS}}{n_{ehcsi,ehcsj}^{EHCS}} \right) + \sum_{ehwsi=1}^{EHWSI} \sum_{ehwsj=1}^{EHW SJ_{ehwsi}} \left( \frac{x_{ehwsi,ehwsj}^{EHW S}}{n_{ehwsi,ehwsj}^{EHW S}} \right) \quad (A.42)$$

$$SEH_{nel,fuel} = \sum_{nehsi=1}^{NEHSI} \sum_{neh sj=1}^{NEHSJ_{neh si}} \left( \frac{x_{neh si,neh sj}^{NEHS}}{n_{neh si,neh sj}^{NEHS}} \right) + \sum_{nehwsi=1}^{NEHWSI} \sum_{nehw sj=1}^{NEHWSJ_{nehw si}} \left( \frac{x_{nehw si,nehw sj}^{NEHWS}}{n_{nehw si,nehw sj}^{NEHWS}} \right) \quad (A.43)$$

$SEH_{el}$  and  $SEH_{nel,fuel}$ : The efficiency of the chosen system for heating

$n_{ehsi,ehsj}^{EHS}$ ,  $n_{ehci,ehcj}^{EHC}$ ,  $n_{ehwi,ehwj}^{EHW}$ : The efficiency (%) of the electrical systems  $ehsj$ ,  $ehcsj$  and  $ehwsj$  of the respected categories  $ehsi$ ,  $ehcsi$  and  $ehwsi$

$n_{neh si,neh sj}^{NEHS}$ ,  $n_{nehw si,nehw sj}^{NEHWS}$ : The efficiency (%) of the non-electrical systems  $neh sj$  and  $nehw sj$  of the respected categories  $neh si$  and  $nehw si$

The annual heating demand can be calculated by summing the demand of each month:

$$Q^{HD} = \sum_{m=1}^{12} Q_m^{HD} \quad (A.44)$$

The heating demand for each month is equal to the sum of heat losses, i.e. monthly transmission  $Q_{T,m}$  (kWh/month) and ventilation losses  $Q_{VEN,m}$  (kWh/month), minus internal heat gains  $Q_{INHG,m}$  (kWh/month) and solar gains  $Q_{SL,m}$  (kWh/month) [16]. Regarding the solar gains only the direct solar gains from window are taken into account and not the indirect (such the absorbance of solar radiation of the walls) despite they might offer a small heat gain [40]:

$$Q_m^{HD} = \begin{cases} HS_m F_{conv} (Q_{T,m} + Q_{VEN,m} - Q_{INHG,m} - Q_{SL,m}), & \text{if positive} \\ 0, & \text{else} \end{cases} \quad (A.45)$$

$$Q_{T,m} = BLC (T_{IH} - T_{o,m}) t_m \quad (A.46)$$

$$Q_{VEN,m} = \rho_{air} c_{pair} ACH \cdot V \cdot (T_{IH} - T_{o,m}) t_m / 3600 \quad (A.47)$$

$$Q_{INHG,m} = (n_{people} Q_{people,m} + Q_{eah,m}) t_m \quad (A.48)$$

$$Q_{SL,m} = \sum_{wn=1}^{WN} \left( A_{wn}^{WIN} F_{F,wn} F_{S,wn} F_{CM,wn} I_{SL,wn,m} t_d \sum_{z=1}^Z \sum_{t=1}^{T_z} (x_{zt}^{WIN} g_{zt}^{WIN}) \right) \quad (A.49)$$

where:

$HS_m$ : Parameter indicating if heating is required for month  $m$  (binary variable with values 1 or 0)

$F_{conv}$ : conversion factor (MJ/kWh)

$BLC$ : Building load coefficient (W/K)

$T_{IH}$ : Internal design temperature for heating season (K)

$T_{o,m}$ : Average external temperature of month  $m$  (K)

$t_m$ : Month duration in hours (h/month)

$t_d$ : Month duration in days (days/month)

$\rho_{air}$ : Air density (kg/m<sup>3</sup>)

$c_{pair}$ : Specific heat of air (kJ/kg K)

$ACH$ : Air changes per hour (h<sup>-1</sup>)

$V$ : Internal Volume of the Building (m<sup>3</sup>)

$A_{wn}^{WIN}$ : Area of window  $wn$  ( $m^2$ ), where  $wn = 1, \dots, WN$

$F_{F,wn}$ : Window frame factor (%)

$F_{SM,wn}$ : Window shading correction factor (%)

$F_{CM,wn}$ : Window correction factor for movable devices (%)

$I_{SL,wn,m}$ : Solar radiation on window  $wn$ , under a certain tilt and orientation ( $kwh/m^2/day$ )

$g_{st}^{WIN}$ : Effective total solar energy transmittance (%) of window sub-type  $t$  of type  $z$

$n_{people}$ : number of people living in the building

$Q_{human,m}$ : Heat emitted per person from radiation ( $W/person$ )

$Q_{eah,m}$ : Heat emitted by electrical equipment

Moreover the BLC of a building can be calculated as:

$$BLC = \sum_{com} A_{com} U_{com} b_{com} \quad (A.50)$$

Where

$com$ : is a building envelope component

$A_{com}$ : surface area ( $m^2$ )

$U_{com}$ : total heat transfer coefficient ( $W/m^2K$ )

$b_{com}$ : temperature correction factor, between 0 for unheated surfaces (e.g. floors or basements)

and 1 for components that face outside air

In detail the BLC is equal to:

$$\begin{aligned} BLC = & \sum_{dr=1}^{DR} (A_{dr}^{DOOR} b_{dr}^{DOOR}) \sum_{d=1}^D (x_d^{DOOR} U_d^{DOOR}) + \sum_{wn=1}^{WN} (A_{wn}^{WIN} b_{wn}^{WIN}) \sum_{z=1}^Z \sum_{t=1}^{T_z} (x_{zt}^{WIN} U_{zt}^{WIN}) \\ & + \sum_{wl=1}^{WL} (A_{wl}^{WALL} b_{wl}^{WALL}) \sum_{w=1}^W (x_w^{WALL} U_w^{WALL}) + \sum_{ce=1}^{CE} (A_{ce}^{CEIL} b_{ce}^{CEIL}) \sum_{r=1}^R (x_r^{CEIL} U_r^{CEIL}) \\ & + \sum_{fl=1}^{FL} (A_{fl}^{FLO} b_{fl}^{FLO}) \sum_{h=1}^H (x_h^{FLO} U_h^{FLO}) \end{aligned} \quad (A.51)$$

In this methodology the overall heat transfer coefficient  $U_{total}$  is used in order to take into account the phenomenon of heat transfer by convection and radiation mechanisms. For doors and windows the manufacturers usually provide the  $U_{value}$  instead of the thermal conductivity and the thickness. For multi-layer components the calculation of the total heat transfer coefficient ( $W/m^2K$ ) takes into account the thickness of each layer, the thermal

conductivity and the inside and outside heat convection coefficient to air. Therefore the following equations are used:

$$U_v^{\text{DOOR}} = \left( \frac{1}{h_i} + \frac{1}{U_{\text{value, door}}} + \frac{1}{h_o} \right)^{-1} \quad (\text{A.52})$$

$$U_w^{\text{WIN}} = \left( \frac{1}{h_i} + \frac{1}{U_{\text{value, win}}} + \frac{1}{h_o} \right)^{-1} \quad (\text{A.53})$$

$$U_w^{\text{WALL}} = \left( \frac{1}{h_i} + \sum_{nwl=1}^{NWL_w} \left( \frac{l_{w, nwl}^{\text{WALL}}}{kk_{w, nwl}^{\text{WALL}}} \right) + \sum_{y=1}^{Y_w} \sum_{p=1}^{P_{wy}} \left( \frac{l_{wyp}^{\text{WALL}}}{k_{wyp}^{\text{WALL}}} x_{wyp}^{\text{WALL}} \right) + \frac{1}{h_o} \right)^{-1} \quad (\text{A.54})$$

$$U_d^{\text{CEIL}} = \left( \frac{1}{h_i} + \sum_{ncl=1}^{NCL_d} \left( \frac{l_{r, kcl}^{\text{CEIL}}}{kk_{r, ncl}^{\text{CEIL}}} \right) + \sum_{f=1}^{F_d} \sum_{a=1}^{A_{df}} \left( \frac{l_{rfa}^{\text{CEIL}}}{k_{rfa}^{\text{CEIL}}} x_{rfa}^{\text{CEIL}} \right) + \frac{1}{h_o} \right)^{-1} \quad (\text{A.55})$$

$$U_h^{\text{FLO}} = \left( \frac{1}{h_i} + \sum_{nfl=1}^{NFL_h} \left( \frac{l_{h, nfl}^{\text{FLO}}}{kk_{h, nfl}^{\text{FLO}}} \right) + \sum_{e=1}^{E_h} \sum_{g=1}^{G_{he}} \left( \frac{l_{heg}^{\text{FLO}}}{k_{heg}^{\text{FLO}}} x_{heg}^{\text{FLO}} \right) + \frac{1}{h_o} \right)^{-1} \quad (\text{A.56})$$

where  $h_i$  and  $h_o$  represent the combined convection radiation coefficients ( $W/m^2K$ )

#### A.2.1.2 Primary Energy Consumption for Cooling

Similarly to the heating energy consumption calculations the total annual primary energy consumption for cooling can be calculated as:

$$Q_C = \frac{Q_{el}^C f^{\text{grid}}}{n_{\text{grid}}} \quad (\text{A.57})$$

Where:

$Q_{el}^C$ : Energy consumed by an electrical system used for cooling (MJ/year)

The energy consumed by an electrical system can be calculated as:

$$Q_{el}^C = Q^{CD} SEC_{el} \quad (\text{A.58})$$

where:

$Q^{CD}$ : The total annual cooling energy demand (MJ/year)

$$SEC_{el} = \sum_{ecsi=1}^{ECSI} \sum_{ecsj=1}^{ECSJ_{ecsi}} \left( \frac{X_{ecsi, ecjsj}^{ECS}}{n_{ecsi, ecjsj}^{ECS}} \right) + \sum_{ehcsi=1}^{EHCSI} \sum_{ehcsj=1}^{EHCSJ_{ehcsi}} \left( \frac{X_{ehcsi, ehcsj}^{EHCS}}{n_{ehcsi, ehcsj}^{EHCS}} \right) \quad (A.59)$$

$SEC_{el}$ : The efficiency of the chosen system providing cooling energy

$n_{ecsi, ecjsj}^{ECS}$ ,  $n_{ehcsi, ehcsj}^{EHCS}$ : The efficiency (%) of the electrical systems  $ecsj$ ,  $ehcsj$  of the respected categories  $ecsi$  and  $ehcsi$

The total annual cooling energy demand can be calculated by summing the cooling energy demand of each month:

$$Q^{CD} = \sum_{m=1}^{12} Q_m^{CD} \quad (A.60)$$

The cooling energy demand for each month is equal to the sum of heat losses, i.e. monthly transmission  $Q_{T,m}$  (kWh/month) and ventilation losses  $Q_{VEN,m}$  (kWh/month), minus internal heat gains  $Q_{INHG,m}$  (kWh/month) and solar gains  $Q_{SL,m}$  (kWh/month). The calculation of cooling energy demand is similar to the one for heating energy demand, but in this case the sol-air temperature is used which takes into account the effect of solar radiation on the outside temperature [27]:

$$Q_m^{CD} = \begin{cases} CS_m F_{conv} (Q_{INHG,m} + Q_{SL,m} - Q_{T,m} - Q_{VEN,m}), & \text{if positive} \\ 0, & \text{else} \end{cases} \quad (A.61)$$

$$Q_{VEN,m} = \rho_{air} c_{pair} ACH \cdot V \cdot (T_{IC} - T_{o,m}) t_m / 3600 + \rho_{air} h_{fg} ACH \cdot V \cdot (w_i - w_{o,m}) t_m / 3600 \quad (A.62)$$

$$Q_{T,m} = BLC (T_{IC} - T_{sol-air,m}) t_m \quad (A.63)$$

$$T_{sol-air,m} = T_{o,m} + \frac{a \cdot \dot{q}_{sol}}{h_o} \quad (A.64)$$

$CS_m$ : Parameter indicating if heating is required for month  $m$  (binary variable)

$T_{IC}$ : Internal design temperature for cooling season (K)

$h_{fg}$ : latent heat of vaporization (usually 2340 kJ/kg)

$w_i$ : Specific humidity indoors ( $\frac{\text{kg}_{\text{wat}}}{\text{kg}_{\text{air}}}$ )

$w_{o,m}$ : Specific humidity outdoors ( $\frac{\text{kg}_{\text{wat}}}{\text{kg}_{\text{air}}}$ )

$T_{\text{sol-air}}$ : Sol-air temperature (K)

$a$ : Absorptivity of the material

$q_{\text{sol}}$ : Solar radiation ( $\text{W}/\text{m}^2$ )

### A.2.1.3 Primary Energy Consumption for Domestic Hot Water

The total annual primary energy consumption for DHW supply would be equal to:

$$Q_{\text{DHW}} = \frac{Q_{\text{el}}^{\text{W}} f^{\text{grid}}}{n_{\text{grid}}} + \sum_{\text{fuel}=1}^{\text{FUEL}} Q_{\text{nel, fuel}}^{\text{W}} \quad (\text{A.65})$$

where:

$Q_{\text{el}}^{\text{W}}$ : Energy consumed by a DHW system using electricity (MJ/year)

$Q_{\text{nel, fuel}}^{\text{W}}$ : Energy consumed by a DHW system using a *fuel*,  $\text{fuel} = 1, \dots, \text{FUEL}$  (MJ/year)

The energy consumption of an electrical and a non-electrical system can be calculated as:

$$Q_{\text{el}}^{\text{W}} = Q^{\text{WD}} \text{SEW}_{\text{el}} \quad (\text{A.66})$$

$$Q_{\text{nel, fuel}}^{\text{W}} = Q^{\text{WD}} \text{SEH}_{\text{nel, fuel}} \quad (\text{A.67})$$

where:

$Q^{\text{WD}}$ : The total annual energy demand for DHW (MJ/year)

$$\text{SEW}_{\text{el}} = \sum_{\text{ewsi}=1}^{\text{EWSI}} \sum_{\text{ewsj}=1}^{\text{EWSJ}_{\text{ewsi}}} \left( \frac{x_{\text{ewsi, ewsj}}^{\text{EWS}}}{n_{\text{ewsi, ewsj}}^{\text{EWS}}} \right) + \sum_{\text{ehwsi}=1}^{\text{EHWSI}} \sum_{\text{ehwsj}=1}^{\text{EHWSJ}_{\text{ehwsi}}} \left( \frac{x_{\text{ehwsi, ehwsj}}^{\text{EHWS}}}{n_{\text{ehwsi, ehwsj}}^{\text{EHWS}}} \right) \quad (\text{A.68})$$

$$\text{SEW}_{\text{nel, fuel}} = \sum_{\text{newsi}=1}^{\text{NEWSI}} \sum_{\text{newsj}=1}^{\text{NEWSJ}_{\text{newsi}}} \left( \frac{x_{\text{newsi, newsj}}^{\text{NEWS}}}{n_{\text{newsi, newsj}}^{\text{NEWS}}} \right) + \sum_{\text{nehwsi}=1}^{\text{NEHWSI}} \sum_{\text{nehwsj}=1}^{\text{NEHWSJ}_{\text{nehwsi}}} \left( \frac{x_{\text{nehwsi, nehwsj}}^{\text{NEHWS}}}{n_{\text{nehwsi, nehwsj}}^{\text{NEHWS}}} \right) \quad (\text{A.69})$$

$\text{SEW}_{\text{el}}$  and  $\text{SEW}_{\text{nel, fuel}}$ : The efficiency of the chosen system providing hot water

$n_{\text{ewsi, ewsj}}^{\text{EWS}}$ ,  $n_{\text{ehwsi, ehwsj}}^{\text{EHWS}}$ : The efficiency (%) of the electrical systems *ewsj* and *ehwsj* of the respected categories *ewsi* and *ehwsi*



$n_{newsi, newsj}^{NEWS}$ ,  $n_{nehwi, nehwi}^{NEHW}$ : Denotes the generation efficiency (%) of the non- electrical systems  $newsj$  and  $nehwsj$  of the respected categories  $newsi$  and  $nehwsj$

The annual DHW energy demand can be calculated by summing the demand of each month:

$$Q^{WD} = \sum_{m=1}^{12} (DQ_m^{DHW}) \quad (A.70)$$

The net DHW demand for each month is equal to the average monthly hot water demand minus the energy a solar collector system provides (in case one is selected):

$$DQ_m^{DHW} = \begin{cases} WS_m F_{conv} (Q_{dhwu, m} - Q_{dSLC, m}), & \text{if } Q_{dhwu, m} \geq Q_{dSLC, m} \\ 0, & \text{else} \end{cases} \quad (A.71)$$

Where:

$WS_m$ : Parameter indicating if DHW is required for month  $m$  (binary variable )

$Q_{dhwu, m}$ : average monthly demand for DHW supply (MJ/month) calculated as:

$$Q_{dhwu, m} = \dot{m}_w \rho_w c_{pw} (T_{DHW} - T_{DCW, m}) t_m \quad (A.72)$$

$\dot{m}_w$ : Rate of consumption of hot water at each day ( $m^3/s$ )

$T_{DHW}$ : The base temperature set for the DHW system (K)

$T_{DCW, m}$ : The temperature of the cold water supply at month  $m$  (K)

$\rho_w$ : The water density ( $kg/m^3$ )

$c_{pw}$ : Specific heat of water ( $kJ/kg K$ )

$Q_{dSLC, m}$ : the monthly hot water demand (MJ/month) provided from a solar collector system (in case one is selected)

$$Q_{dSLC, m} = F_{conv} A_{SLC} F_{S, SLC} I_{SL, SLC, m} t_d \sum_{slci=1}^{SLCI} x_{slcj, slci}^{SLC} n_{slcj, slci}^{SLC} \quad (A.73)$$

$A_{SLC}$ : Area of solar collector ( $m^2$ )

$F_{S, SLC}$ : Correction factor for shading (%)

$I_{SL, SLC, m}$ : Solar radiation incident on a solar collector type  $slcj$  of category  $slci$ , under a specific tilt and orientation ( $kwh/m^2/day$ )

$n_{slcj, slci}^{SLC}$ : efficiency of a solar collector type  $slcj$  of the category  $slci$  (%)

#### A.2.1.4 Primary Energy Consumption for Lighting

The total annual primary energy consumption for lighting purposes is calculated as:

$$Q_L = \frac{Q_{el}^L f^{grid}}{n_{grid}} \quad (A.74)$$

where:

$Q_{el}^L$ : is the annual electrical energy consumed for lighting (MJ/year)

The electrical energy consumption for providing lighting is equal to:

$$Q_{el}^L = Q^{LD} SEL_{el} \quad (A.75)$$

where:

$Q^{LD}$ : Total annual demand for electricity for lighting (MJ/year)

$SEL_{el} = 1$ , assuming no losses of electricity from supply to consumption

The annual energy demand for lighting can be calculated by summing the demand of each month:

$$Q^{LD} = \sum_{m=1}^{12} Q_m^{LD} \quad (A.76)$$

It is assumed that the lamps would be operating the same number of hours each day and consequently all the months of the year. The energy consumption of lamps can be calculated as:

$$Q_m^{LD} = F_{conv} t_d \sum_{l=1}^L (P_{L,l} f_{use,l}) \sum_{li=1}^{Ll} \sum_{lj=1}^{Llj} x_{li,lj}^L \quad (A.77)$$

$l = 1, \dots, L$ : Number of lamps

$P_{L,l}$ : Lamp power rating (kW)

$f_{use,l}$ : Time that the device is used (h/day)

#### A.2.1.5 Primary Energy Consumption for Electrical appliances

The total annual primary energy consumption for the operation of the electrical appliances is calculated as:

$$Q_A = \frac{Q_{el}^A f^{grid}}{n_{grid}} \quad (A.78)$$

Where:

$Q_{el}^A$ : is the annual energy (electricity) consumed for operation of electrical appliances (MJ/year)

The electrical energy consumed for operation of electrical appliances is:

$$Q_{el}^A = Q^{AD} SEA_{el} \quad (A.79)$$

Where:

$Q^{AD}$  : Total annual demand for electricity for operation of electrical appliances (MJ/year)

$SEA_{el} = 1$ , assuming no losses of electricity from supply to consumption

The annual energy demand for the operation of electrical appliances can be calculated by summing the demand of each month:

$$Q^{AD} = \sum_{m=1}^{12} Q_m^{AD} \quad (A.80)$$

It is assumed that the electrical appliances would be operating the same number of hours each day and consequently all the months of the year. The energy consumption of electrical appliances can be calculated as:

$$Q_m^{AD} = F_{conv} t_{d,m} \sum_{eai=1}^{EAI} \left( P_{A,eai} f_{use,eai} f_{load,eai} \sum_{eaj=1}^{EAI} X_{eai,eaj}^{EA} \right) \quad (A.81)$$

$P_{A,a}$ : Electric appliance power rate (W)

$f_{use,a}$ : Time that the device is used (h/day)

$f_{load,a}$ : Load factor of the device (%)

#### A.2.1.6 Electricity supply

The total annual demand for electrical energy is equal to the electricity consumption for heating, cooling, DHW, lighting, and operation of the electrical appliances:

$$Q_{EL}^D = Q_{el}^H + Q_{el}^C + Q_{el}^W + Q_{el}^L + Q_{el}^A \quad (A.82)$$

The annual electricity demand of the electrical systems consists of the average demand for electricity supply from the grid  $Q_{el,grid}$ , reduced by the electricity provided by a RES system  $Q_{el,alt}$ , in case one is selected and is operating:

$$Q_{el, alt} = \sum_{resi=1}^{RESI} \sum_{resj=1}^{RESI_{ehci}} Q_{el, resi, resj} X_{resi, resj}^{RES} \quad (A.83)$$

Where

$Q_{el,resi,resj}$ : electricity generation from a RES system  $resj$  of category  $resi$  (MJ/year)

The renewable sources that could be used to provide electricity are solar energy (photovoltaic systems) or wind energy (wind turbines). Moreover, it is further assumed that all the electricity generated from RES would be either used in the building or exported to the grid [32]. Therefore, the total supply from the grid would be equal to:

$$Q_{el, grid} = \begin{cases} (Q_{EL}^D - Q_{el, alt}), & \text{if } Q_{EL}^D > Q_{el, alt} \\ 0, & \text{else} \end{cases} \quad (A.84)$$

### A.2.2 Initial Investment Cost

As it was mentioned before, several approaches regarding the cost have been made in such models. Similarly to [16] in this model the initial investment cost is used which is defined as the initial cost of acquisition of the components and the cost of installation. The initial investment cost for the proposed components would be equal to:

$$\begin{aligned} INVCOST = & COST_{DOR} + COST_{WIN} + COST_{WAL} \\ & + COST_{CEIL} + COST_{FLO} + COST_{HS} \\ & + COST_{CS} + COST_{WS} + COST_{HCS} \\ & + COST_{HWS} + COST_{SLC} + COST_{RES} \\ & + COST_{LIGHT} + COST_{EA} \end{aligned} \quad (A.85)$$

Independently, the cost for each component can be calculated as:

$$COST_{DOR} = \sum_{dr=1}^{DR} (A_{dr}^{DOOR}) \sum_{d=1}^D (x_d^{DOOR} C_d^{DOOR}) \quad (A.86)$$

$$COST_{WIN} = \sum_{wn=1}^{WN} (A_{wn}^{WIN}) \sum_{s=1}^S \sum_{t=1}^{T_s} (x_{st}^{WIN} C_{st}^{WIN}) \quad (A.87)$$

$$COST_{WAL} = \sum_{wl=1}^{WAL} (A_{wal}^{WAL}) \sum_{w=1}^W \left( x_w^{WAL} \left( \sum_{nwl=1}^{NWL_w} (CK_{w, nwl}^{mWALL}) + \sum_{y=1}^{Y_w} \left( \sum_{p=1}^{P_{wy}} (x_{wyp}^{mWALL} C_{wyp}^{mWALL}) \right) \right) \right) \quad (A.88)$$

$$COST_{CEIL} = \sum_{ce=1}^{CE} (A_{ce}^{CEIL}) \sum_{d=1}^D \left( x_d^{CEIL} \left( \sum_{ncl=1}^{NCL_r} (CK_{d, ncl}^{mCEIL}) + \sum_{f=1}^{F_r} \left( \sum_{a=1}^{A_{rf}} (x_{rfa}^{mCEIL} C_{rfa}^{mCEIL}) \right) \right) \right) \quad (A.89)$$

$$COST_{FLO} = \sum_{fl=1}^{FL} (A_{fl}^{FLO}) \sum_{h=1}^H \left( x_h^{FLO} \left( \sum_{nfl=1}^{NFL_h} (CK_{h, nfl}^{mFLO}) + \sum_{e=1}^{E_h} \left( \sum_{g=1}^{C_{he}} (x_{heg}^{mFLO} C_{heg}^{mFLO}) \right) \right) \right) \quad (A.90)$$

$$COST_{HS} = \sum_{ehsi=1}^{EHSI} \sum_{ehsj=1}^{EHSJ_{ehsi}} (x_{ehsi,ehsj}^{EHS} CST_{ehsi,ehsj}^{EHS}) + \sum_{nehsi=1}^{NEHSI} \sum_{nehsj=1}^{NEHSJ_{ehsi}} (x_{nehsi,nehsj}^{NEHS} CST_{nehsi,nehsj}^{NEHS}) \quad (A.91)$$

$$COST_{CS} = \sum_{ecsi=1}^{ECSI} \sum_{ecsj=1}^{ECSJ_{eci}} (x_{ecsi,ecsj}^{ECS} CST_{ecsi,ecsj}^{ECS}) \quad (A.92)$$

$$COST_{WS} = \sum_{ewsi=1}^{EWSI} \sum_{ewsj=1}^{EWSJ_{ewi}} (x_{ewsi,ewsj}^{EWS} CST_{ewsi,ewsj}^{EWS}) + \sum_{newsi=1}^{NEWSI} \sum_{newsj=1}^{NEWSJ_{ehi}} (x_{newsi,newsj}^{NEWS} CST_{newsi,newsj}^{NEWS}) \quad (A.93)$$

$$COST_{HCS} = \sum_{ehcsi=1}^{EHCSI} \sum_{ehcsj=1}^{EHCSJ_{ehci}} (x_{ehcsi,ehcsj}^{EHCS} CST_{ehcsi,ehcsj}^{EHCS}) \quad (A.94)$$

$$COST_{HWS} = \sum_{ehwsi=1}^{EHWSI} \sum_{ehwsj=1}^{EHW SJ_{ehwi}} (x_{ehwsi,ehwsj}^{EHWS} CST_{ehwsi,ehwsj}^{EHWS}) \quad (A.95)$$

$$+ \sum_{nehwsi=1}^{NEHW SI} \sum_{nehwsj=1}^{NEHW SJ_{ehwsi}} (x_{nehwsi,nehwsj}^{NEHWS} CST_{nehwsi,nehwsj}^{NEHWS})$$

$$COST_{SLC} = \sum_{slci=1}^{SLCI} \sum_{slcj=1}^{SLCJ} \left( x_{slci,slcj}^{SLC} CST_{slci,slcj}^{SLC} \right) \quad (A.96)$$

$$COST_{RES} = \sum_{resi=1}^{RESI} \sum_{resj=1}^{RESJ_{ehci}} \left( x_{resi,resj}^{RES} CST_{resi,resj}^{RES} \right) \quad (A.97)$$

$$COST_{LIGHT} = L \sum_{li=1}^{LI} \sum_{lj=1}^{LJ_{li}} \left( x_{li,lj}^L CST_{li,lj}^L \right) \quad (A.98)$$

$$COST_{EA} = \sum_{eai=1}^{EAI} \sum_{eaj=1}^{EAJ_{eai}} \left( x_{eai,eaj}^{EA} CST_{eai,eaj}^{EA} \right) \quad (A.99)$$

Where,

$C_v^{DOOR}$ : the initial investment cost for a door of type  $d$  (£/m<sup>2</sup>)

$C_{zt}^{WIN}$ : the initial investment cost for a window of sub-type  $t$  of type  $z$  (£/m<sup>2</sup>)

$CK_{w,nwl}^{mWALL}$ ,  $CK_{r,ncl}^{mCEIL}$ ,  $CK_{h,nfl}^{mFLO}$ : the initial investment costs for the materials used in the known layers  $nwl$ , of wall structure  $w$ ,  $ncl$  of ceiling structure  $r$  and  $nfl$  layers of floor structure  $h$  (£/m<sup>2</sup>)

$C_{wyp}^{mWALL}$ ,  $C_{rfa}^{mCEIL}$ ,  $C_{heg}^{mFLO}$ : the initial investment costs for the material  $p$  that is used in the unknown layer  $y$  of wall structure  $w$ , the material  $a$  that is used in the unknown layer  $f$  of ceiling structure  $r$  and the material  $g$  that is used in the unknown layer  $e$  of floor structure  $h$  (£/m<sup>2</sup>)

$CST_{ehsi,ehsj}^{EHS}$ ,  $CST_{nehsj,nehsi}^{NEHS}$ : the initial investment cost for the electrical heating system  $ehsj$  of category  $ehsi$  and the non-electrical heating system  $nehsj$  of category  $nehsi$  (£)

$CST_{ecsj,ecsi}^{ECS}$ : the initial investment cost for the electrical cooling system  $ecsj$  of category  $ecsi$  (£)

$CST_{ewsj,ewsi}^{EWS}$ ,  $CST_{newsj,newsi}^{NEWS}$ : the initial investment cost for the electrical DHW system  $ewsj$  of category  $ewsi$  and the non-electrical DWH system  $newsj$  of category  $newsi$  (£)

$CST_{ehcsj,ehcsi}^{EHCS}$ : the initial investment cost for the electrical heating-cooling system  $ehcsj$  of category  $ehcsi$  (£)

$CST_{ehwsi, ehwsj}^{EHWS}$ ,  $CST_{nehwsi, nehwsj}^{NEHSW}$ : the initial investment cost for the electrical heating-DHW system  $ehwsj$  of category  $ehwsi$  and the non-electrical heating-DWH system  $nehwsj$  of category  $nehwsi$  (£)

$CST_{slci, slcj}^{SLC}$ : the initial investment cost for the solar collector system  $slcj$  of category  $slci$  (£)

$CST_{resi, resj}^{RES}$ : the initial investment cost for the RES electricity system  $resj$  of category  $resi$  (£)

$CST_{li, lj}^L$ : the initial investment cost for the lamp  $lj$  of category  $li$  (£)

$CST_{eai, eaj}^{EA}$ : the initial investment cost for the electrical appliance  $eaj$  of category  $eai$  (£)

### A.3 Objective Functions

#### A.3.1 The Case of a New Building

In order to determine the optimal prioritization of the energy efficiency measures in a new building, the primary energy consumption and the initial investment cost criteria must be minimized according to the procedure described in subsections A.2.1 and A.2.2 respectively:

$$\begin{aligned} \min [g_1(\mathbf{x})] &= Q_T \\ \min [g_2(\mathbf{x})] &= \text{INVCOST} \end{aligned} \tag{A.100}$$

*Subject to*

Constraints: (A.1) - (A.99)

#### A.3.2 The Case of Retrofitting an Existing Building

For the case of retrofitting an existing building the methodology is similar to that of a new building. However, in this case the objectives would be to achieve maximum primary energy savings with minimal initial investment cost. Therefore, the primary energy consumption of the existing building before any retrofit action must be calculated.

The primary energy consumption of an existing building is calculated with the methodology described in subsection A.2.1. However, in this case there are no decision variables. Also, the constraints regarding the components of the building's envelope as were set in subsection A.2.1 might not apply as an existing building theoretically might have more than one type of doors, windows etc. The procedure used in Section A.2.1 is followed similarly:

The total annual primary energy consumption of an existing building can be calculated using equation (A.38) and is equal to:

$$Q_{T\_pre} = Q_H + Q_C + Q_{DHW} + Q_L + Q_A \quad (\text{A.101})$$

Where:

$Q_{T\_pre}$ : The annual primary energy consumption before any retrofit action.

Moreover, it is assumed that an existing building before retrofit would not have RES to provide electrical energy.

To calculate the primary energy consumption after the retrofit actions ( $Q_{T\_post}$ ) on a building the procedure in subsection A.2.1 is followed again. Moreover, it is assumed that in the case of retrofitting an existing building the wall, ceilings and floor structures would not be changed. Hence, the decision variables (A.5), (A.9) and (A.10) have already value equal to 1. Insulation layers may exist in some components but also they could be applied to the other components.

The initial investment cost of the components for retrofitting a building, represents the cost acquisition and installation of the proposed components and can be calculated similarly to subsection A.2.2. The variables  $CK_{w,kwl}^{mWALL}$ ,  $CK_{d,kcl}^{mCEIL}$  and  $CK_{d,kfl}^{mFLO}$  are equal to 0 as they already exist.

The criteria to find the best solution are the energy savings and the initial cost of the investment. In this case energy savings must be maximized and the investment cost must be minimized:

$$\begin{aligned} \max [g_1(\mathbf{x})] &= Q_{T\_pre} - Q_{T\_post} \\ \min [g_2(\mathbf{x})] &= \text{INVCOST} \end{aligned} \quad (\text{A.102})$$

*Subject to*

Constraints: (A.1) - (A.99), except those excluded in this subsection.

Given that  $Q_{T\_pre}$  is a constant parameter of the model, the first objective function of (101) is actually equivalent to the first objective function of (99).

## Appendix “B”

Available online.



## **Appendix “C”**

Available online.