Multi-Objective Optimisation In Early Stage Design. Case Study: Northampton University Creative Hub Building

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Abstract

The aim of this paper is to investigate optimum design options for the early design stage of a building that would not only result in achieving low carbon status, but could also have a reduced construction capital cost.

During the last decade, there has been an increasing interest in using optimisation algorithms in the building design process. However, in real-world building design complications, the optimisation problem consists of at least two conflicting objectives, e.g. minimising energy demand whilst keeping the construction cost low without compromising the user's comfort. In this case study, a commercial variant of the well-known genetic algorithm NSGA II was used to identify a set of optimal solutions. DesignBuilder software was utilised to create the base model and run the multi-objective optimisation, with two objectives; energy consumption and capital cost.

The optimisation results represent the design balance between capital cost and energy consumption. The design solutions that help maintain the comfort performance have been derived from a rationalisation exercise that was undertaken prior to this study and aligns thermal comfort with a defined industry guidance including minimising the quantified risk of overheating and excessive energy use for cooling.

Introduction

In order to achieve the 80% CO_2 reduction target by 2050, the UK government has signed and is legally bound by the UNFCCC Framework and Kyoto protocol agreements. In addition, the UK is forced under the EU proposal Directive to a 20% more energy efficient building infrastructure (Grubb et al., 2008).

The building sector is the largest user of energy in the European Union. Hence, the need to improve the design of new buildings is critical. In the UK, according to the national statistics (DECC, 2014), 30% of the energy consumption and 35% of the total electricity was consumed within the buildings sector.

Passive strategies, energy efficiency methods and innovative building services technologies, are well discussed and established within this research field. However, the decision making process to identify the best combination that would result in the best possible scenario is not a straightforward practice. There are numerous features, which need to be harmonised, such as: financial, social, legal and energy & environmental etc. (Asadi et al., 2012).

There is evidence in literature that the early stage design decisions for new builds will highly influence the building performance over at least the first 50 years of their lifetime (Negendahl et al., 2015).

In the building performance modelling research community, the term 'optimisation' has a different meaning to different researchers. The optimisation exercise is either treated as a technique to find a global optimum to a defined problem through sensitive and qualitative analysis alone (Heiselberg, 2009) or it is performed by implementing a numerical simulation and mathematical optimisation to derive the optimal solution to an objective problem (Nguyen, 2014). Furthermore, optimisation problems can be categorised as one-dimensional or multi-dimensional optimisation, depending on the number of design variables in action.

In this research work, optimisation is considered as a combination of a qualitative and quantitative analysis – rationalisation that leads to an automated process, which is entirely based on numerical simulation and mathematical optimisation. This method is usually automated by the combination of a building simulation program and an optimisation "machine" which contains an optimisation algorithm.

In particular, the authors approach is following the multi-objective optimisation that is proposed by Pareto. A solution is non-dominated when there is no other feasible solution that advances one objective without weakening the other one. The multi-objective algorithm product is a set of non-dominated solutions that is termed 'Pareto Front' (Machairas et al, 2014).

The Case Study Building

The University of Northampton located in the United Kingdom (UK) is in the process of extending its campus to include six additional buildings as shown on the architectural master plan in Figure 1.

Figure 1: Architectural master plan of the development. University of Northampton campus layout and selected building location.

The design for the buildings had been developed to RIBA Stage 3, where upon completion, a contract for construction is issued typically based on competitive tender. The design then underwent a value engineering exercise to attempt to reduce the project capital cost to align with the client budget. This presented an excellent opportunity to undertake a case study of the application of a parametric optimisation using the updated DesignBuilder software. Of the six buildings, a medium sized multi-function building, The Creative Hub, was selected for this case study.

The Creative Hub at the University of Northampton is a five-story building with a floor area of 10,000 m^2; a 3D Revit generated design model representation is shown in Figure 2. The building architectural scheme reflects a variety of spaces, including breakout spaces, teaching facilities, rehearsal and performance spaces, as well as functional circulation and services spaces.

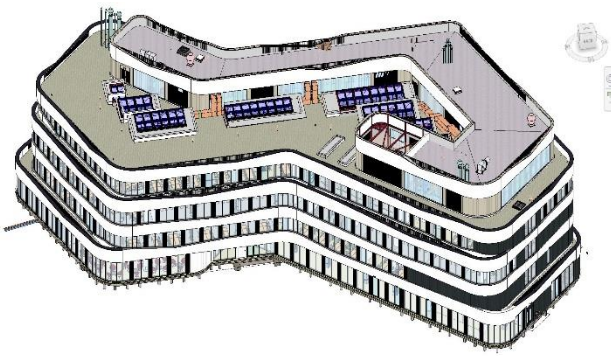

Figure 2: Creative Hub building 3D model.

Since the case study building is located in the UK, the design must comply with Building Regulations including Approved Document Part L2A (Building Regulations 2010). The building is also targeting an Energy Performance Certificate (EPC) rating of “A”. The Target Emission Rate (TER) has been derived based on a dynamic model as 18.0 $kgCO_2/m^2$ while the resulting Building Emission Rate (BER) is 14.6 $kgCO_2/m^2$ which also reflects a predicted “A” rating for the EPC. In addition, The Creative Hub building is required to achieve a Building Research Establishment Environmental Assessment Methodology (BREEAM) rating of “Excellent”.

The Optimisation Methodology

A thermal model was developed for the simulation of the energy consumption of the building and it is defined by parameters that represent physical aspects of the building. Variable values for those parameters were used to define building fabric construction, services, and operation of the building.

In order to explore a very large number of building variants in a relatively short time, the implemented approach contains the following:

(i) identifying the design variables to be optimised

(ii) describing the options and the range of variation for each parameter

(iii) running the energy simulation of the building in free-running mode using a simulation tool

The energy simulations of the building were run with the software EnergyPlus version 8.5 (Crawley et al, 2001) using DesignBuilder version 5.0.1.024 as an interface.

The optimisation run was achieved by using the DesignBuilder software through the non-dominated genetic algorithm NSGA-II (Deb et al., 2002). The optimisation module utilises an advanced evolutionary algorithm analysis platform to assimilate building performance design variables through a natural selection process to meet the design objectives. The optimum design solutions are identified and inherited to subsequent generations and continue to do so until the optimum design synergies have been determined based on the design constraints applied. In order to build up the optimisation run, the steps include:

(i) specifying the design variables, their variation ranges and the optimisation algorithm

(ii) examining the variants that minimise capital cost, considering the objective functions related to energy performance

As previously mentioned, one of the key steps in the optimisation process is to select parameters that represent aspects of the building design that would benefit from optimisation and a suitable range of variables that should be applied to those parameters (Fesanghary et al., 2012). In this study, a team of academics, engineers and quantity surveyors carefully selected design options translated in kWh/m^2 and £/m^2 for the following parameters:

1. External wall and roof construction
2. Glazing
3. Lighting system
4. HVAC (Heating Ventilation and Air Conditioning) system
5. Shading strategy

In combination with the following limitations:

a. The shape of the building and the façades to be retained as specified by the architect.
b. The layout of the building to be simplified by merging similar activity zones to decrease the computational time.

Design Variables

Within the optimisation function of DesignBuilder, the overall cost is based on the construction cost. This estimation is based on market prices in July 2016, and implemented into the software by the authors. This cost value includes the supply of materials and labour cost for installation with an additional contingency percentage, but excludes the main contractor's preliminaries, overheads, profit, design fees and VAT.

Rationalisation Prior to Optimisation

One of the main attractions of optimisation is that it assures the simultaneous evaluation of the effects of different conflicting design parameters. For example, increasing the glazing area could increase the energy demand for cooling by allowing more solar gain into a space. However, greater glazing area could decrease the amount of energy required by reducing the need for lighting and increasing the potential opportunity to apply natural ventilation and passive cooling strategies. The advantage of multi-objective optimisation is that all the parameters are evaluated simultaneously and a range of optimal solutions can be established in terms of the objectives: cost and energy consumption. In order for the optimisation process to identify the optimum solutions, the authors consider the "rationalisation prior to optimisation" exercise is critical to allow the algorithm to identify the Pareto optimal trade-off between conflicting design objectives such as capital cost and operational energy usage.

Rationalisation was applied by analysing the room operational requirements and identifying suitable environmental conditions in reference to CIBSE recommended design practices. This exercise informed the design team to allow the baseline building services systems to be defined in terms of Heating Ventilation and Air Conditioning (HVAC) and lighting systems. For example, for circulation spaces, the background heating and ventilation has been consistently applied as a zoning solution, as shown in Table 4.

Environmental Comfort Performance

Comfort performance analysis has been provided in reference to indoor environment design indicators specified in European Standard BS EN 15251 (British Standard Institute EN 15251, 2007) in terms of thermal criteria, air quality, humidity, lighting and acoustic performance. This applies to both the reference design and the optimisation study. Assessment of the internal environment is based on the thermal environment and resultant comfort performance for a mechanically heated and/or cooled building for a Category II application, which is defined as having a 'normal level of expectation adopted for new buildings' (BSI, 2007). It should be noted that detailed analysis related to comfort performance is not the focus of this study and is beyond the scope of this paper.

Building Fabric

The design variables related to the building fabric consisted of external wall construction, glazing, window to wall ratio and shading. In this particular building, the façade and hence the window to wall ratio was fixed and based on architectural specification as well as the shading which was based off the landscape architect specification. The external wall and roof constructions were specified in the architect's design specification with options for alternative solutions being constrained by aesthetic considerations.

For the case study, this resulted in the options for exterior wall construction to be limited to variations in the thickness of the insulation layer, constrained by Building Regulations compliance. Consequently, in this optimisation study, two types of external walls have been considered, an opaque wall construction with mineral fibre as the insulation media and an opaque wall with polyurethane insulation. The only variant is the thickness of the insulating layer. The overall costs and build-ups for the exterior wall constructions are shown in Table 1.

Table 1: External wall and roof construction variables and variation range

External wall and roof insulation	Commercial available thickness (mm)	Calibrated U-Value (W/m^2K)	Cost (£/m^2)
Opaque wall Internal insulation – mineral fiber	210	0.099	1480
	140	0.145	1390
	100	0.197	1320
	75	0.254	1300
	60	0.307	1290
Opaque wall Internal insulation – polyurethane	210	0.099	1570
	140	0.145	1500
	100	0.197	1430
	75	0.254	1380
	60	0.307	1360
Roof Insulation - polyurethane	200	0.104	250
	130	0.145	210
	100	0.197	190
	75	0.254	190
	60	0.307	180

Initially, each of the two final exterior wall constructions were imported to the model with a range of U-Values between 0.15 W/m^2K and 0.35 W/m^2K and a step increment of 0.05 W/m^2K. However, in practise, insulation thickness is constrained by commercially available sizes. Consequently, the fabric U-values have been calibrated to reflect the commercial procurement with respect to cost and thermal performance for both the external walls and the roof construction.

Glazing consisted of 6 options with different U-values taking into account light transmittance (LT) and solar energy transmittance (G-value), details can found in Table 2.

Table 2: Glazing design variables and variation range

Glazing Description	g-value	LT - Value	Ug-Value (W/m^2K)	Cost (£/m^2)
(1a) Pilkington Optifloat Bronze	0.41	0.32	1.0	60
(1b) Pilkington Optifloat Grey	0.37	0.31	1.0	60
(2a) Pilkington Suncool 70/35	0.37	0.69	1.0	80
(2b) Pilkington Suncool Silver 50/30	0.31	0.49	1.0	80
(3) Pilkington SuncoolBlue 50/27	0.28	0.49	1.1	80
(4) Pilkington Suncool 30/16	0.18	0.4	1.1	85

For the lighting design, there are four different options which have been considered. T16 fluoresent open plan lighting and LED open plan lighting, both with and without daylight control. The cost of the options vary from 70 £/m^2 to 84 £/m^2 and are shown in Table 3.

Table 3: Lighting options and costs

Lighting solution	Total cost
(1) T16 fluorescent	£70/m^2
(2) T16 fluorescent with daylighting control	£75/m^2
(3) LED	£79/m^2
(4) LED with daylighting control	£84/m^2

HVAC systems can be divided into natural ventilation systems, which provide ventilation directly via openings in the façade and mechanical ventilation systems, which provide ventilation using mechanical plant. There is a third category called "mixed mode" in which maximum use of natural ventilation is made with supplementary assistance of mechanical ventilation under conditions where natural ventialtion alone is impractical due to design constraints.

In the current version of the DesignBuilder software, there is a limitation factor of ten parameters for optimisation. This means that at the absolute most, there could only be ten types of zoning where options for combinations of HVAC systems could be applied. This would need to decrease to allow simultaneous multi-objective optimisation with other parameters such as building fabric construction, lighting system and glazing selection.

Because of the number of solutions being high and the constraints of the software, it was clear that the HVAC solutions needed to be rationalized. This was also likely to have benefits in terms of value engineering for the project even before any optimisation analysis was carried out. Hence the zones were rationalised to six options: O, A, B, C, D and E, all with different combinations of HVAC systems. A system breakdown of these zones is shown in Table 4.

Table 4: Zoning of the HVAC solutions

Zone and treatment options	*O*	*A*	*B*	*C*	*D*	*E*
(0)Background heating and ventilation	✓					
(1)Displacement		✓	✓	✓	✓	✓
(2) Secure vents chilled beams and displacement			✓			
(3) Minimum fresh air and variable refrigerant flow		✓	✓	✓	✓	
(4) Secure vents, radiators and displacement				✓	✓	
(5) Secure vents, under floor heating and displacement					✓	
(6) Variable air volume		✓	✓	✓	✓	✓
(7) Minimum fresh air and fan coil units		✓	✓	✓	✓	
(8) Minimum fresh air, radiators and chilled beams		✓	✓	✓	✓	

Figure 3 below shows how the derived solutions were applied on the first Floor of the Creative Hub building as an indicative example of this exercise.

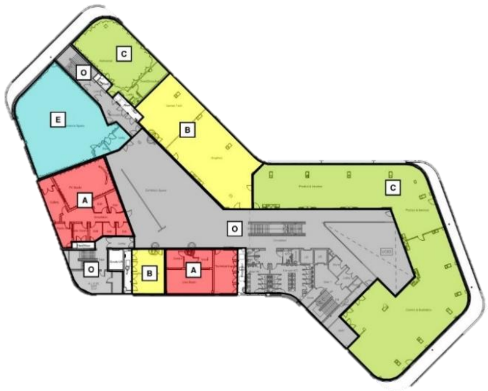

Figure 3. First Floor Ventilation system philosophy

The cost parameters of the selected HVAC systems for the optimisation run can be found in Table 5 below.

Table 5: Cost of the HVAC variables

HVAC solution	Total cost
No treatment	£0/m^2
Displacement	£275/m^2
Minimum fresh air and variable refrigerant flow	£300/m^2
Variable air volume	£345/m^2
Minimum fresh air and fan coil units	£365/m^2
Secure vents, chilled beams and displacement	£495/m^2
Secure vents under-floor heating and displacement	£495/m^2
Secure vents radiators and displacement	£505/m^2
Minimum fresh air, radiators and chilled beams	£555/m^2

Table 6 indicates the solution space size as a product of all the parameters and their limitations after the rationalisation exercise the authors went through to minimise non-dominant solutions and to drive the dominant ones to the right direction towards a feasible design outcome. As it can be seen from this table, with a number of parameters and relatively small number of variations of each, the total number of possible designs for single building, increased very quickly to over 8,000,000. It is not common practise in the design industry for a team to search this solution space exhaustively, as a point-to-point search would last a very long time and could easily lock into a local suboptimum design. On the other hand, the amount of time taken by simulation tools to run the evaluations to find an optimum solution is high and a powerful computer is definitely required to perform these runs. In this particular research study, an optimisation run of approximately 5000 iterations of the discussed optimisation problem took approximately 180 hours to complete on an 8-core 3.50GHz Intel PC. This limits the use of simulation tools for real time control applications but at least it is obvious that it is a time effective solution in comparison with the value engineering exercises.

Table 6: Possible solutions space

Parameter	Options
External wall 02	5
External wall 04	5
Roof construction	5
Glazing	7
Lighting	4
HVAC Zone A	5
HVAC Zone B	6
HVAC Zone C	6
HVAC Zone D	7
HVAC Zone E	2
The solution space	**8,820,000**

Results & Discussion

The results output of the optimisation simulation performed in the DesignBuilder software is shown in Figure 4. The optimisation algorithm used in this study recalled only realistic solutions - those meeting the constraints - for the final Pareto set. Analysis of unrealistic solutions is also useful in providing information on areas of the solution space to avoid for future reference.

The 15 Pareto design solutions highlighted in red which form the Pareto Front, are the most practical solutions for capital cost vs site energy consumption. The reference design is highlighted in blue.

As shown in Figure 4, the engineered reference solution is close to the Pareto Front but there are other solutions that achieve the same energy consumption with a lower capital cost. Thus the optimisation successfully provides a superior solution than the actual reference design for the Creative Hub.

Table 7 summarises the design variable combinations of the reference case, the solution that achieves the minimum energy consumption, the solution that achieves the minimum capital cost and the selected practical solution from the Pareto Front. It demonstrates that although an improved building fabric performance achieves minimum energy consumption, a more average building fabric can be more cost effective providing a similar saving in energy.

LED lighting seems to dominate the Pareto solutions but the benefit of the daylight dimming in energy consumption is not cost effective. This could be the result of the building orientation and building form being pre-defined. In addition, the glazing type optimisation was applied on a building level, meaning daylight control would not have been utilised based on orientation.

A different glazing type than the reference case provides better results for the majority of the Pareto Front solutions. The HVAC system options for the reference case are in correlation with the minimum energy consumption solution while the displacement heating and cooling system seem to be the most efficient in the practical solution and most of the Pareto Front solutions as the results show in Table 8 in the Appendix.

The above points reveal that optimisation at an early stage in the design would have taken the building services design down a substantially different design path. The potential benefits of applying design optimisation to a project greatly outweigh the additional engineering design input required. Applying optimisation as a design tool is most beneficial during early design development stages where project specific objectives and constraints can inform design decisions and propagate through the design process. Since design solutions are typically informed based on cost as a primary driver, developing representative cost data and understanding and interpreting design cost synergies is critical.

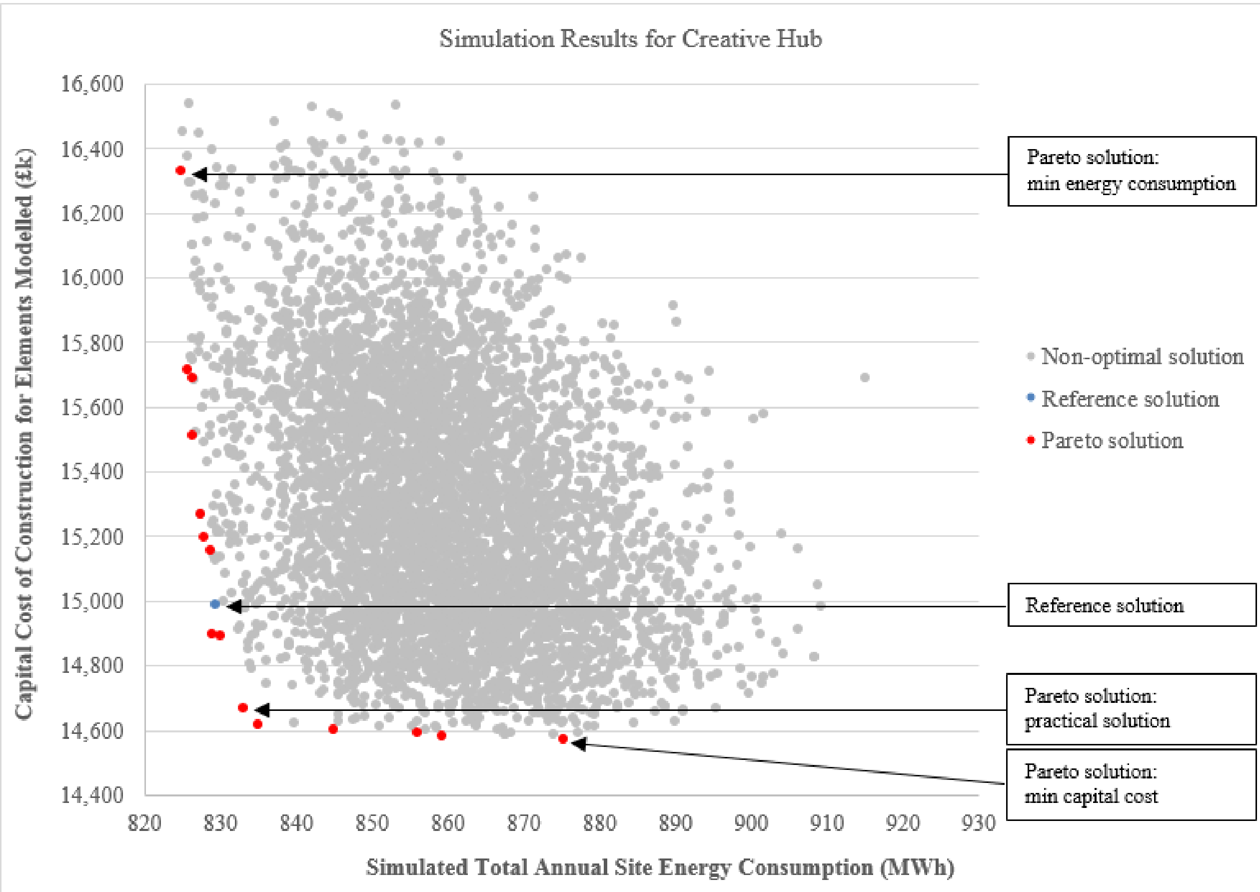

Figure 4: Results for optimisation simulations of the Creative Hub

Table 7: Summary of the key results for the reference and the selected Pareto solutions

Parameter	Ref Design	Pareto Solution		
		Min Energy Consumption	Min Capital Cost	Practical Solution
Simulated annual energy consumption (kWh)	829,327	824,767.74 (-4,559)	875,117.7 (45,791)	835,030.18 (5,703)
Simulated construction cost (£)	14,987,356	16,328,368 (1,341,012)	14,569,758 (-417.598)	14,619,173 (-368,183)
External wall construction Type 4 ($W/m^2.K$)	0.197	0.099	0.197	0.254
External wall construction Type 2 ($W/m^2.K$)	0.197	0.099	0.307	0.254
Flat roof construction ($W/m^2.K$)	0.197	0.104	0.307	0.197
Lighting template	LED linear/off control	LED no control	T16mm Fluorescent, no daylight control	LED no control
Glazing type	1a - Pilkington Optifloat Bronze	2a-Pilkington Suncool 70/35	2b-Pilkington Suncool Silver 50/30	2a-Pilkington Suncool 70/35
HVAC Zone A	1 Displacement heating & cooling	1 Displacement heating & cooling	1 Displacement heating & cooling	6 VAV
HVAC Zone B	2 Secure vent, displacement heating & chilled beam	8 Min FA, radiators, chilled beams	1 Displacement heating & cooling	1 Displacement heating & cooling
HVAC Zone C	2 Secure vent, displacement heating & chilled beams	4 Secure vent, displacement, radiators	3 Min FA + VRF	1 Displacement heating & cooling
HVAC Zone D	5 Secure vent, UFH, displacement	5 Secure vent, UFH, displacement	1 Displacement heating & cooling	1 Displacement heating & cooling
HVAC Zone E	6 VAV	6 VAV	1 Displacement heating & cooling	1 Displacement heating & cooling

Conclusion

Further simulations are needed in order to establish whether the practical solution accomplishes similar performance under Part L2A Building Regulations compliance and similar thermal comfort as the engineered reference case.

The optimisation results successfully provide a solution of lower capital cost whilst sustaining a comparable energy performance against the base reference solution. The final practical result of optimisation illustrates construction savings of 2.5% (£368,183) whilst maintaining a similar annual energy consumption (<0.01% difference of 5703KWh) in comparison with the reference design choice.

From this computational study, it can be concluded that am optimisation run should be done at an early stage of the design process to influence the major parameters affecting energy efficiency and capital cost. The optimisation module of the DesignBuilder software enables the user to run multiple combinations of design options that in common engineering practice would be very time consuming and commercially unsustainable. The optimum solutions identified can then be further interrogated if they are feasible to be applied in the building design. This optimisation process offers greater assurance from early stage design that that the best solution is implemented.

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Appendix

Table 8: Reference and Pareto Front Results

Parameter	Ref. Design	Pareto Solution														
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Simulated annual energy consumption (MWh)	921.9	824.8	825.7	826.2	826.4	827.4	827.8	828.7	828.9	829.9	833.1	835.0	845.0	855.9	859.2	875.1
Simulated construction cost (£M)	14.99	16.33	15.72	15.69	15.51	15.27	15.20	15.16	14.90	14.89	14.67	14.62	14.60	14.59	14.58	14.57
External wall construction Type 4 ($W/m^2.K$)	0.197	0.099	0.197	0.254	0.254	0.254	0.254	0.099	0.197	0.254	0.254	0.254	0.254	0.254	0.197	0.197
External wall construction Type 2 ($W/m^2.K$)	0.197	0.099	0.099	0.099	0.099	0.145	0.197	0.197	0.197	0.197	0.254	0.254	0.254	0.307	0.307	0.307
Flat roof construction ($W/m^2.K$)	0.197	0.104	0.104	0.104	0.145	0.104	0.104	0.104	0.104	0.104	0.145	0.197	0.307	0.254	0.307	0.307
Lighting template	4	3	4	3	3	3	3	3	3	3	3	3	4	3	3	1
Glazing type	1a	2a	2a	2a	2a	2a	2a	2a	2a	2a	2a	2a	2a	1a	3	2b
HVAC Zone A	1	1	1	1	1	1	6	7	1	1	6	6	1	1	1	1
HVAC Zone B	2	8	2	8	1	1	1	6	1	8	1	1	3	6	3	1
HVAC Zone C	2	4	1	1	1	6	1	1	1	1	1	1	1	1	1	3
HVAC Zone D	5	5	5	5	4	6	4	6	6	1	1	1	1	1	1	1
HVAC Zone E	6	6	1	1	1	1	6	6	1	1	1	1	1	1	1	1