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Optimisation of Building's Construction Costs and CO_2 Emission Based on the Computer Model of a Theoretical Office Building Located Near London

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Abstract – **The results of the building optimisation presented in this article come from the author's entry project in the Design Optimisation Competition 2014. Simulations were conducted to help to design an office building and to minimise its costs and impact on the environment. Ultimately, the building's construction costs were reduced to £2,294,216 and annual CO_2 production to 136,169.3 kg, while maintaining discomfort hours below 200 hours per year and daylight floor area above threshold on the level of 60.0 %.**

Keywords – **Building optimisation, CO_2 emission, construction costs.**

Building industry uses about 50 % of all raw materials processed in the world. Concurrently, almost 50 % of the total invested capital in the developed countries is tied up in the housing sector. It means that reduction in construction and exploitation costs as well as in environmental damage is essential in latter-day building industry [1], [2]. The economy is strictly bounded with the quantity of natural resources, and money – substitute of material value, always corresponds with the usage of those resources. This relation is described by energy embodied in economic value indicator [3] which shows the amount of energy put into investment at a given moment. This indicator does not determine economic profitability but rather helps to estimate the ecological effect – the less money we spend on the building, the better for the environment.

In addition to the logical reasons for reducing building's costs and environmental damage, there are also global and local legislation and regulations regarding the building industry, which improve energy efficiency, implement new low-carbon energy sources and taxation of pollutions. One of the most significant treaty for reducing global pollution emission was the Kyoto Protocol from 1997, which implemented targets based on a system of "carbon trading" between nations. The Kyoto Protocol results in EU Emission Trading Scheme and pollution market, where one (typically "rich developed") country buys "carbon credits" from another (typically "poor developed") country [2]. Since the pollution translates directly into CO_2 emission, the limitation of carbon emissions became profitable. The effects of this policy can be seen in building industry in the United Kingdom, where improvements in buildings are expected to make significant contribution to CO_2 reduction targets. To meet this requirement, many of the building projects are optimised with help of simulation software.

Nowadays there are numerous computer programs in which the building's geometry as well as heating, cooling or ventilation systems can be analyzed. These tools enable simulation and optimisation of various building's systems, such as passive solar heating, solar ventilation air preheat, photovoltaic or solar water heating. For architects most interesting may be the programs which help to create proper passive solar heating systems which directly influence the architecture. There is a number of different programs: COMFIE, DEROB-LTH, DOE-2, Energy Plus, Energy Scheming, ESP-r, Hot2 XP, RETScreen, Solacalc, SUNREL, SOLAR-5, TRNSYS and Window 4.1 which are all well tested and have comprehensive documentation [4]. Some of these programs are used also for design and analysis of other building's systems such as photovoltaic: TRNSYS and RETScreen. The most convenient program for architects, from these mentioned above, is Energy Plus [5]. It is non-proprietary, provides visible and well-described calculations, has extensive weather data and is constantly developed and updated. What is more, it has many user-friendly interfaces, which are developed by private companies, e.g. Design Builder, Autodesk Green Building Studio, ECOTECT or SolarShoeBox. Design Builder is one of the best such interfaces because it displays building's geometry, thickness of partitions and windows or doors. It is possible to construct there the building's model anew or to import building's information from CAD program [6]. The building's optimisation process in the Design Builder program is described in this article.

The results of the office building optimisation presented in this article come from the author's entry project in the Design Optimisation Competition (DOC) 2014 organised by the Design Builder Software and De Montfort University (UK). The purpose of the competition was the utilisation of simulation software during the design process in order to minimise environmental impact, development costs and simultaneously satisfy the minimum level of occupant comfort and daylighting [7], [8].

I. Methods

The Design Optimisation Competition simulated a real-world design scenario in which a client provides a request for an early design model of the office building. All simulations were made in Design Builder V4.1.0.005 Beta. The plot intended for the office building was located near Gatwick Airport in London (UK) (Fig. 1), (Fig. 2). Required building's total floor area amounted to 3,000 (±1 %) m^2 and was divided into four zones – open office (min. 2,080 m^2), cellular office (min. 320 m^2 inclusively, each room max. 30 m^2), utility (min. 420 m^2) and circulation (reminder), which were separately analysed in the Design Builder. The settings for each zone type are listed in Table I. There was no restriction on the number of stories or floor area per storey [8], [9].

TABLE I
SETTINGS FOR EACH ZONE TYPE [8].

Zone type	Equipment [W/m²]	People/m²	Target Lux	Fresh Air [l/s-person]	Setpoints
Generic Office Area	11.77	0.111	400	10	Adjustable
Utility areas	5.48	0.1124	200	12	
Circulation areas	1.85	0.1173	100	10	

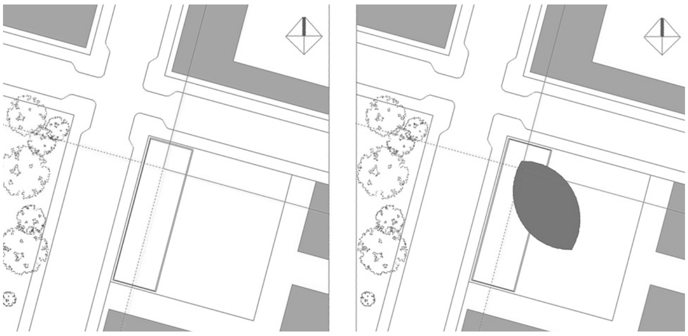
a). b).

Fig. 1. Building's location: a) the plot near Gatwick airport, b) building's situation [7], [8].

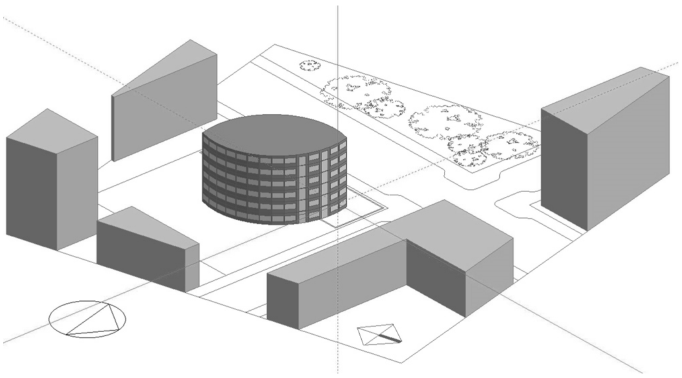
Fig. 2. Axonometry – a model from Design Builder [7], [8].

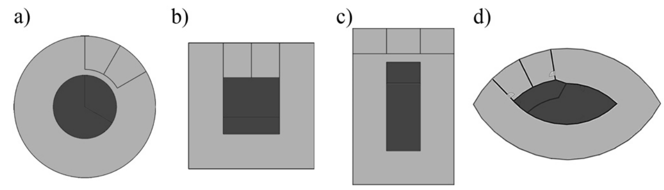

Fig. 3. Different shapes of core-ring construction: a) circular, b) square, c) rectangular, d) "lemon" [Author of the Article].

Due to the competition restrictions only certain data could be edited in the model. The file with the example baseline model contained the components and templates, each with assigned cost.

Carbon emission was calculated based on the building's fuel consumption for heating, cooling and for the operation of other equipment such as lights and computers. The carbon emission factors are standard values for the UK [8].

The estimated building construction cost data was based on "per gross internal floor area" costs of services, sub-structure and frame construction, whereas the cost of other constructions, glazing and surface finish was based on the "per surface area" cost. All costs were calculated using the inbuilt Design Builder costing tool.

During occupied periods the building should be comfortable for occupants with no more than 200 hours of discomfort. Calculations should be based on ASHRAE 55 (ANSI/ASHRAE Standard 55-2010: Thermal Environmental Conditions for Human Occupancy) [10], [11].

The building should have daylight factor greater or equal to 2 % – the floor area above threshold (%) over at least 50 % of the floor area. This factor is assessed through radiance us- ing the CIE overcast sky and working plane height of 0.75 m.

The 2014 edition of the DOC was the second edition of this competition. It was allowed to use previous submissions (DOC 2012), analyse solutions and implement them into the projects. Nonetheless, entirely new form of building was chosen in this project.

II. SIMULATIONS AND OPTIMISATION

To reduce the simulation time, design tasks have been divided into several smaller problems, i.e. construction materials, window size or heating system, and each of them has been considered separately. For the sake of brevity only several exemplary simulations are presented. They are divided into a few thematic groups; numbers of experiments show chronological order of simulations, but they do not create sequence.

A. Form and construction

The first requirement was to provide sufficient amount of daylight for the office area. Core-ring construction (Fig. 3) enables the creation of two zones – inner, without daylight, where utility and circulation area can be situated, and outer zone with open space and cellular offices. Due to no waste of space near the windows the daylight is used efficiently.

On one hand, to lower the building's cost, external surface should be minimised to decrease the heat transfer. Lowering the area of façade minimises thermal bridging and reduces costs of the façade. On the other hand the bigger the façade and the windows area, the better daylighting and ventilation. Considering the building's cost and heat transfer, the best shape for the building would be sphere, which has the smallest surface area to volume ratio (SA/V) [12]. However, for the inexpensive building it is easier and cheaper to use a right prism as a building form. Question remains, in what shape should be the base face of the right prism and how many storeys it should have. Consid-

Table II
Building With Square Base [Author of the Article].

Number of floors	Single floor area [m²]	Facade area [m²]	Total area of external surface [m²]	Ring width [m]
5	600.00	1567.67	2767.67	6.8
6	500.00	1717.30	2717.30	6.2
7	428.57	1854.90	2712.04	5.7
8	375.00	1982.97	2732.97	5.4

Table III
Building With Circular Base [Author of the Article].

Number of floors	Single floor area [m²]	Facade area [m²]	Total area of external surface [m²]	Ring width [m]
5	600.00	1389.31	2589.31	7.6
6	500.00	1521.92	2521.92	7.0
7	428.57	1643.86	2501.00	6.5
8	375.00	1757.36	2507.36	6.0

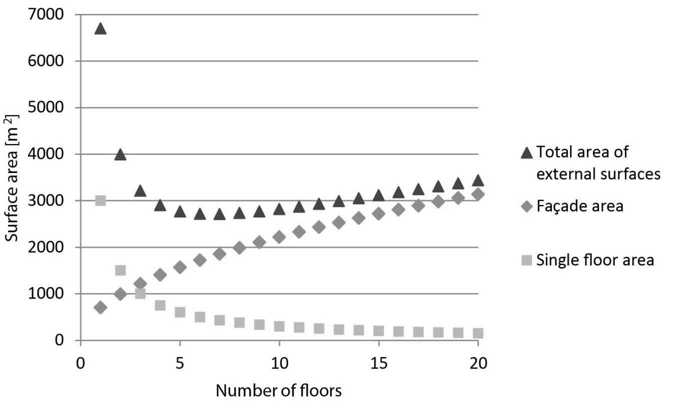

Fig. 4. Relationship between the number of floors and surface areas in square building [Author of the Article].

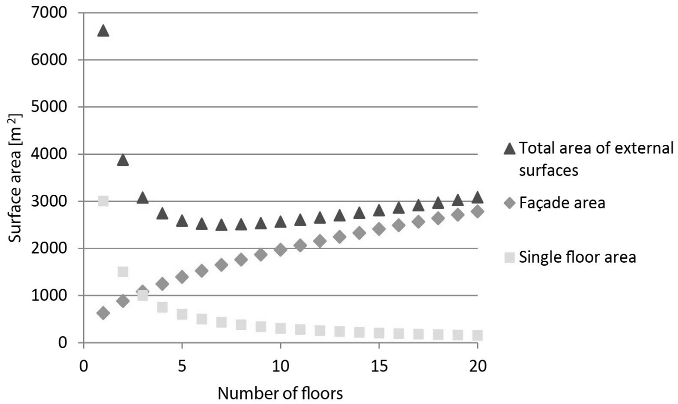

Fig. 5. Relationship between the number of floors and surface areas in circular building [Author of the Article].

ering the relationship between the perimeter and area (PA ratio) the circle has the smallest PA of all surfaces and the square – of all rectangles. The relationships between the number of storeys, façade area and total area of external surface (façade area + roof area + ground floor area) in buildings with square and circular base are presented in Table II, Table III and in Fig. 4 and Fig. 5. For simplification, it was assumed that the roof and ground floor areas are the same as the single floor area. The façade area was calculated as a product of single floor perimeter, storey height (3.2 m) and number of storeys.

In both buildings – with square and circular base, the lowest total area of external surface is when they are 7 storeys high. However, there is a significant difference between them in the size of the external surface area. "Square" building has 211.04 m² larger external surface area than the "circular" building, while having the same cubature. Seemingly smaller external area is better but it also means smaller area for windows, i.e. daylight and natural ventilation. For this reason an intermediate solution was found – "lemon" – a mix of circular and square shape (Fig. 6), which has two huge façades exposed in a favourable direction and only two edges, which minimise thermal bridging (Table IV), (Fig. 7).

The width of the ring which embraces the building's core is at the same time the depth of open space and office rooms. As the depth of the room increases (normally 5–7 m) the intensity of daylight in the room diminishes [13]. Since the usage of the special prisms which redirect the light so that the room is equally illuminated was not allowed, maximal depth of the room was 7 m. Simultaneously, creating open space which is shallower than 6–7 m is a waste of daylight. Consequently, a 6-storey "lemon" building was chosen with 1617.79 m² façade area, 2617.79 m² total area of external surface and 6.3 m ring width. Cellular offices for managers were placed equally on every floor, except the ground floor, where there was only one cellular office and a large entrance area (Fig. 8), (Fig. 9).

TABLE IV
A Building with "Lemon" Shape Base [Author of the Article].

Number of floors	Single floor area [m²]	Facade area [m²]	Total area of external surface [m²]	Ring width [m]
5	600.00	1467.20	2667.20	7.0
6	500.00	1617.79	2617.79	6.3
7	428.57	1756.83	2613.97	5.8
8	375.00	1889.79	2639.79	5.4

TABLE V
The Best Construction Solutions and Materials From DOC 2012 [7].

Submission 109	Hardwood 2.54 cm – OSB (oriented strand board) 2.2 cm – 2 x 10 cm mineral wool batt – OSB 2.2 cm (all materials and their prices are listed in DOC Brief).
Submission 018	Cement sand render 2 cm – concrete lightweight block 20 cm – mineral wool quilt 10 cm – PCM Q27 (2 phase change material, which melts above 27 °C) 0.6 cm – plasterboard 1.3 cm.

TABLE VI
Final Design Constructions and Materials Used in Further Simulations [Author of the Article].

Light frame construction	Cement sand render 2 cm – OSB 2.2 cm – air gap 5 cm – mineral wool batt 2 x 10 cm – OSB 2.2 cm. Cost per m²: £48
Roof	Asphalt 1 cm – mineral fibre board preformed 10 cm – 2 x 10 cm mineral wool batt – OSB 2.2 cm. Cost per m²: £53
Ground floor	Concrete 10 cm – EPS (Expanded Polystyrene) 10 cm – flooring screed 7 cm – timber flooring 3 cm. Cost per m²: £100
Internal partitions	Light construction – OSB and insulation filling. Cost per m²: £20

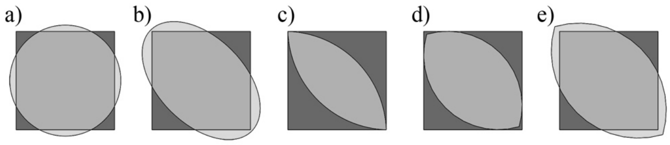

Fig. 6. a) - e) Evolution of the building into the 'lemon' shape [Author of the Article].

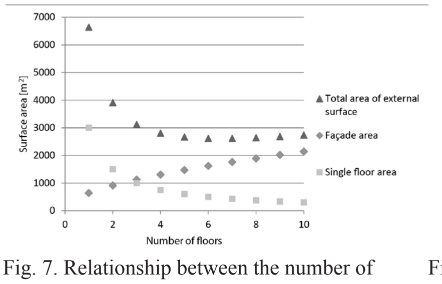

Fig. 7. Relationship between the number of floors and surface areas in "lemon" building [Author of the Article].

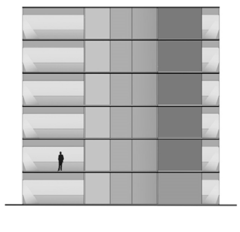

Fig. 8. Cross section A-A of the "lemon" building [Author of the Article].

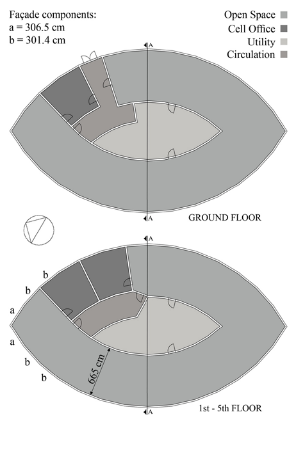

Fig. 9. Floor plans of the "lemon" building [Author of the Article].

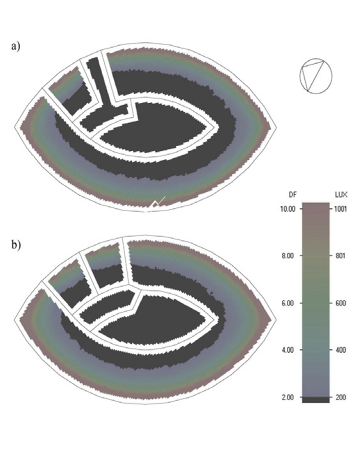

Fig. 10. Daylight distribution on the 1st (a) and 5th (b) floor [Author of the Article].

B. Construction materials

Construction materials were chosen at the beginning of the optimisation process because they do not influence other parameters. This experiment was conducted with chosen settings which did not affect the results – only the comparative difference in the results between the tested materials was important. Two best façade constructions and materials used in models in DOC 2012 (Table V) were applied in the model, simulated and then the better one was used in further simulations.

Roof, ground floor and internal partition construction and materials were chosen in the same way as the façade (Table VI).

C. Openings

Competition regulations allowed to choose the type of window glazing: double or triple, filled with air or argon, with low emissivity glass (Low-E) or uncoated. There was no constraint regarding the window to wall ratio (WWR) or window height, width or sill height. As a window shading, a blind with low, medium or high reflectivity, shade roll, overhangs or louvres could be selected. Only one type of ventilation was provided – grille, small, light slats. Internal and external doors had to be included in the model, with at least one external door on the ground floor [8]. Experiments with different options of openings (Table VII), daylight analyses and

TABLE VII
EXPERIMENTS WITH DIFFERENT OPTIONS OF OPENINGS [AUTHOR OF THE ARTICLE].

Experiment 1. Window to wall ratio					
	WWR [%]	Total cost [£]	CO_2 emission [t/yr]	Discomfort [hrs/yr]	Daylight [%]
a).	40	2,319,30	147.89	621	51.3
b).	45	2,352,658	146.15	655	54.4
c).	50	2,385,887	145.16	697	64.4
Experiment 3. Window glazing types with WWR 45 %					
	Double Glazing	Total cost [£]	CO_2 emission [t/yr]	Discomfort [hrs/yr]	Daylight [%]
a).	Argon	2,365,510	177.21	203	56.5
b).	Air	2,343,734	179.05	203	56.6
Experiment 5. Window to wall ratio with lighting system from Experiment 4					
	WWR [%]	Total cost [£]	CO_2 emission [t/yr]	Discomfort [hrs/yr]	Daylight [%]
a).	43	2,330,441	131.98	170	54.4
b).	45	2,341,512	131.91	172	56.2
c).	50	2,376,963	131.21	176	69.0
Experiment 6. Window size with WWR 45 %					
	Window type	Total cost [£]	CO_2 emission [t/yr]	Discomfort [hrs/yr]	Daylight [%]
a).	Same size of all windows	2,318,196	137.73	186	56.2
b).	Porte-fenêtre in cell office	2,320,573	136.13	189	56.5

TABLE VIII
LIGHTING SYSTEM EXPERIMENT [AUTHOR OF THE ARTICLE].

Experiment 4. T5 and LED lighting source with daylight control, WWR 43%					
	Lighting source	Total cost [£]	CO_2 emission [t/yr]	Discomfort [hrs/yr]	Daylight [%]
a).	T5	2,330,441	178.41	202	54.5
b).	LED	2,424,075	176.44	206	56.6

TABLE IX
COMPETITION HVAC SYSTEMS [AUTHOR OF THE ARTICLE].

a).	Fan-coil unit
b).	LTHW radiator heating with natural ventilation
c).	Passive chilled beams, displacement ventilation and LTHW radiators
d).	Air source heat pump (heating only), floor heating and natural ventilation
e).	Ground source heat pump (heating only), floor heating and natural ventilation
f).	Variable refrigerant flow (VRF) as heating/cooling, plus dedicated outdoor air systems (DOAS) with heat recovery
g).	Variable air volume (VAV) with terminal reheat

daylight distribution (Fig. 10) are presented below. The experiments were not conducted with the same settings, only each experiment separately was conducted with the chosen settings.

D. Lighting systems

Several lighting systems were available: compact fluorescent lamp (CFL) with no control, T5 fluorescent tube with or without linear control and LED, also with or without control. A lighting control sensor in each zone was defined automatically [8]. T5 and LED lighting sources where checked with the daylight control system applied in open space and cellular offices (Table VIII).

E. HVAC systems

In this competition the term "HVAC" covers mechanical heating and cooling as well as natural ventilation [8]. Seven types of HVAC and different heating and cooling operation schedules were provided (Table IX). It was forbidden to use dehumidification/humidification tool to improve thermal comfort. Natural ventilation in HVAC systems is used both for cooling and for providing fresh air for occupants' respiration. The natural ventilation air is delivered through openable windows and vents controlled by a thermostat [8].

In the building's model the best results were brought by HVAC system with low temperature hot water (LTHW) radiator and natural ventilation.

F. Control systems

The maximum allowed area of openable windows for natural ventilation was 20 % [8]. Any control schedule could be selected or created for windows and vents. In Table X the experiments of setpoint temperatures and building's location on the plot are presented.

TABLE X
Competition HVAC Systems [Author of the Article].

Experiment 2. Setpoint temperatures					
Settings for cooling: cooling temperature 25 °C and cooling set back 28 °C. Order of setpoints below: heating temperature, heating set back and natural ventilation set back					
	Setpoints	Total cost [£]	CO_2 emission [t/yr]	Discomfort [hrs/yr]	Daylight [%]
a).	22, 16, 24	–	177	202	–
b).	22, 18, 23	–	200	199	–
c).	22, 16, 25	–	166	209	–
Experiment 7. Building's location on the plot (Fig. 11)					
	Location	Total cost [£]	CO_2 emission [t/yr]	Discomfort [hrs/yr]	Daylight [%]
a).	In the middle of the plot	2,293,442	135.91	202	–
b).	Pivoted	2,293,358	135.81	204	–
c).	Moved	2,293,358	134.00	202	–

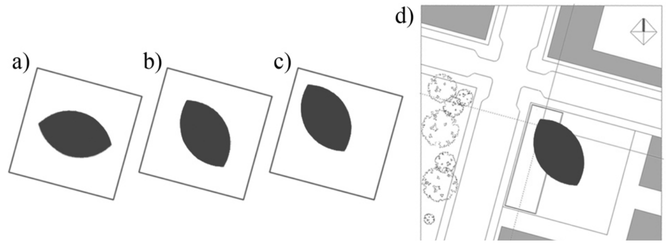

Fig. 11. Building's location on the plot [Author of the Article].

Results and Conclusions

According to the multistage project optimisation, the building's total construction cost was reduced to £2,294,216 and annual CO_2 production to 136,169.3 kg (in comparison to £2,745,000 and 297,470 kg for the reference building presented by DOC organisers), while maintaining discomfort hours below 200 hours per year and daylight floor area above threshold on the level of 60.0 %.

The best project in DOC 2012 cost £2,474,000 and had annual CO2 emission on the level of 136,179 kg, whereas in DOC 2014 it was £2,469,000 and 86,230 kg respectively. The final design is presented in Table XI, Fig. 12 and Fig. 13.

Core-ring construction used in the project comprises outer "ring" space, where all rooms requiring daylighting can be situated. Owing to this solution, it was feasible to achieve 60 % daylight floor area above threshold indicator, which is one of the best results in the competition. This proves that core construction is indeed appropriate for the office buildings – it creates perfect conditions for work and reduces the expenses for artificial lighting. The next step in decreasing CO_2 emission may include modification of façade construction, maintaining the accomplished cost level. Further improvement in the reduction of CO_2 emission can be achieved by using photovoltaic panels as a source of energy or PCM as an insulation material.

In this article, the optimisation of the model of a theoretical office building in simulation program is presented. It was conducted in the Energy Plus interface – Design Builder, which is perfect for the optimisation process, as it uses parametric analysis and genetic algorithms. However, the model created on the

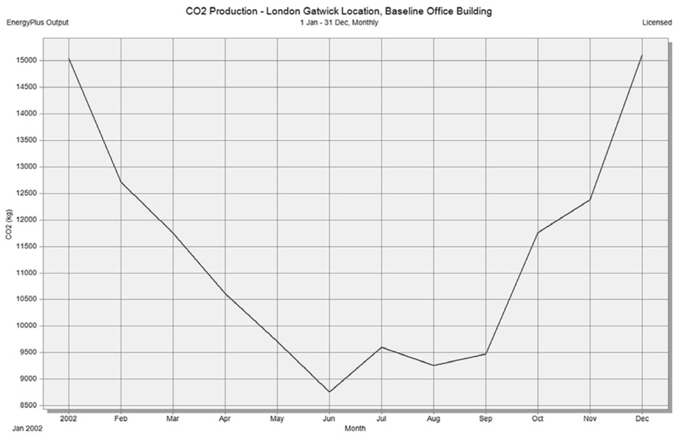

Fig. 12. Building's annual CO_2 production [Author of the Article].

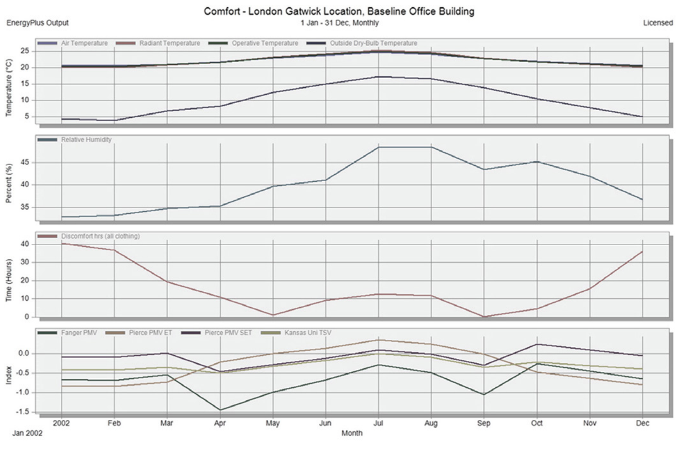

Fig. 13. Comfort in the building [Author of the Article].

grounds of the idea or early project which is sufficient in the building's design and optimisation stage may not imitate ideally the real future building's behaviour. This is why the models are often calibrated with real buildings – measured and simulated indoor temperatures are compared and building's parameters properly adjusted. Later, credible models are used in simulations of alternative solutions.

TABLE XI

FINAL DESIGN OF FLOOR AREAS, MATERIALS AND SETTINGS [AUTHOR OF THE ARTICLE].

Floor areas	Total floor area [m^2]	3002.97
	Office floor area [m^2]	2409.38
	of which cellular office area [m^2]	326.18
	Utility area [m^2]	431.32
	Circulation area [m^2]	162.27
Construction	Light frame construction	Cement sand render 2 cm – OSB 2.2 cm – air gap 5 cm – mineral wool batt 2 x 10 cm – OSB 2.2 cm. Cost per m^2: £48
	Roof	Asphalt 1 cm – mineral fibre board preformed 10 cm – 2 x 10 cm mineral wool batt – OSB 2.2 cm. Cost per m^2: £53
	Ground floor	Concrete 10 cm – EPS (Expanded Polystyrene) 10 cm – flooring screed 7 cm – timber flooring 3 cm. Cost per m^2: £100
	Internal partitions	Light construction – OSB and insulation filling. Cost per m^2: £20
Openings	Windows	44 % WWR, preferred window height 1.5 m, sill height 0.9 m.
		Glazing type: double, filled with air, Low-E.
		Window frame – painted, wooden.
		Shading – outside blind with high reflectivity slats, control type – horizontal solar, operation schedule ON.
		Opening position right, 20 % glazing area opens, operation schedule – open office (adjusted to normal work week).
	Doors	External and internal doors: 100 % – area of open doors and 100 % – time of open doors, schedule – open office.
	Vents	Grille, small, light slats.
Lighting	T5 fluorescent – with linear daylight control in office rooms, without control in utility and circulation zone.	
HVAC	LTHW radiator heating and natural ventilation, schedule – open office Heating – work days 5.00 – 19.00 "1"(100 %), other hours and weekend "0.5"(50 %)	
	Domestic hot water (DHW) – open office schedule	
	Natural ventilation – calculated, schedule ON Modulate openings areas – lower value of Tin-Tout (delta °C) 5, upper value of Tin-Tout (delta °C) 18	
	Environmental control	Heating 22 °C and heating set back 12 °C, cooling 25 °C and cooling set back 28 °C, natural ventilation 23 °C.

References

1. **Hegger, M., Fuchs, M., Stark, T., Zeumer, M.** *Energy Manual : Sustainable Architecture.* Basel, Boston, Berlin: Birkhäuser, 2008. 280 p. (English translation of the 1st German edition; translated by G. H. Söffker, P. Thrift and P. Seidel) ISBN: 978-3-7643-8830-0.
2. **Edwards, B.** *Rough guide to sustainability : A design primer.* London: RIBA, 2014. pp. 43–47.
3. **Cebrat, K.** Wskaźnik energii wbudowanej w pieniądz : Drugie spojrzenie na koszty budowy. *Rynek instalacyjny.* 2014/3. pp. 63–66. (Energy embodied in economic value indicator : A second glance at investment cost).
4. **Walker, A.** *Solar Energy : Technologies and project delivery for buildings.* Hoboken: Wiley, 2013. pp. 267–272. http://dx.doi.org/10.1002/9781118842973
5. Energy Plus Program [online]. *U.S. Department of Energy : Energy Plus* [cited 23.10.2015]. http://apps1.eere.energy.gov/buildings/energyplus/
6. Design Builder Software [online]. *Design Builder* [cited 23.10.2015]. http://www.designbuilder.co.uk/
7. Design Optimisation Competition official web site [online]. *Optimisation Competition* [cited 13.09.2014]. http://optimisationcompetition.org
8. Competition Brief and User's Guide [online]. *Optimisation Competition* [cited 13.09.2014]. http://optimisationcompetition.org/wiki/doku.php?id=2014:downloads
9. Design Builder Manual [online]. *Design Builder* [cited 13.09.2014]. http://www.designbuilder.co.uk/helpv4.0/
10. *ASHRAE Green Guide : The design, Construction and Operation of Sustainable Buildings.* Amsterdam, Boston, Heidelberg etc.: Elsevier. 2010. 464 p. (American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc.) ISBN: 978-1-933742-85-4.
11. **Bauer, M., Mösle, P., Schwarz, M.** *Green Building : Guidebook for Sustainable Architecture.* Berlin, Heidelberg: Springer, 2010. 209 p. ISBN: 978-3-642-00634-0.
12. Perimeter and area [online]. *Argyll Centre* [cited 13.09.2014]. http://staff.argyll.epsb.ca/jreed/math9/strand3/formulae.htm
13. **Neufert, E., Neufert, P.** *Architects' Data.* Oxford: Blackwell Science, 2000. 648 p. (3rd ed., edited by B. Baiche and N. Walliman). ISBN: 0-632-05771-8.

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