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ScienceDirect
Energy Procedia 78 (2015) 2899 – 2904
Energy Procedia

6th International Building Physics Conference, IBPC 2015

An approach to urban quarter design using building generative design and thermal performance optimization

Eugénio Rodrigues[a,b,*], Ana Rita Amaral[a],
Adélio Rodrigues Gaspar[a], Álvaro Gomes[b,c]

[a]*ADAI, LAETA, Department of Mechanical Engineering, University of Coimbra, Rua Luís Reis Santos, Pólo II, 3030-788 Coimbra, Portugal*
[b]*INESC Coimbra – Institute for Systems and Computer Engineering at Coimbra, Rua Antero de Quental 199, 3000-033 Coimbra, Portugal*
[c]*Deparment of Electrical and Computer Engineering, University of Coimbra, Rua Luís Reis Santos, Pólo II, 3030-290 Coimbra, Portugal*

Abstract

Buildings thermal performance is influenced by the urban context, such as adjacent buildings shadows, block wind paths, or solar radiation reflection. For this reason, in this paper, an automated procedure is used to generate and optimize buildings' thermal performance in a closed O-shape urban quarter with ten building blocks to determine the importance of including the surroundings in estimating the buildings' thermal behavior. The overall shape of the urban quarter is pre-designed, being mainly residential, with several stores in the ground floor and limited to three levels. Each building will have four alternative designs created using a hybrid evolutionary strategy technique that generates building's floor plans according to practitioner's preferences and requirements. Then, a sequential variable optimization procedure coupled with dynamic simulation engine is used to explore the improvement potential of each solution by changing and adding several building elements. The final quarter design is determined by combining the best of all buildings' solutions from thermal performance criteria.

The results demonstrate the influence of urban context in the resulting building's thermal performance. Despite the building's shape is similar in the four solutions, these have significant thermal behavior difference due to their interior organization and position in the urban quarter. A comparison analysis is carried out between all building block designs. The buildings, which have exterior walls with openings facing south, have almost half degree-hours of thermal discomfort due to the combination of large openings and shading overhangs. It is also possible to conclude that generative tools, enhanced with optimization procedures, may help practitioners in designing more energy efficient buildings.

Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL

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* Corresponding author. Tel.: +351 962719008.
E-mail address: eugenio.rodrigues@gmail.com (Eugénio Rodrigues)

Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL
doi:10.1016/j.egypro.2015.11.662

Keywords: urban generative design; building thermal performance; dynamic simulation; geometry optimization

1. Introduction

The built environment is responsible for 31% of the global energy consumption, with space heating and cooling representing 30% (in cold climates up to 60%) [1]. The building performance depends significantly from its surroundings, thus it is crucial to assess and improve the urban form. The best way to determine the building performance taking into account all the elements brought by the urban context that may influence is to use dynamic simulation. Moreover, several approaches have presented this dynamic simulation coupled to performance optimization techniques as a path to optimize the solutions achieved, in an early stage of the design process. Each approach intends to focus on different criteria.

As Vermeulen et al. [2] show, the combination of simulation tools with numerical optimization methods appears to be an efficient way to obtain the best option for each case, according to defined objectives and requirements. This research team coupled a hybrid evolutionary algorithm to an urban energy simulator (CitySim) focused on radiation and buildings energy flows, pursuing an evaluation of annual energy needs, defined as the objective function to be minimized in the optimization process. Koenig [3] used simulation techniques based on cellular automata to generate complex urban patterns, combining the six which he considered the most common. In this way, alternative solutions were created for the same design problem in a short time and in an easy way, as the experiments were created in CAD environment. Kämpf and Robinson [4] used the solar irradiation criterion to apply an evolutionary algorithm as a building optimization to the program RADIANCE, in order to obtain the best building and urban form to predict urban solar potential for use, namely through solar thermal collectors or photovoltaic panels.

Summing up, and according to Sanaienan et al. [5], an extensive review on recent research can lead the prediction of the effect of urban form on buildings performance to the aggregation into three categories: the thermal behavior, solar access for passive heating and daylight purposes, and indoor and outdoor natural ventilation. However, this study showed how difficult it is to analyze the impact of the surroundings on buildings thermal performance, leading researchers to focus on the parameter with more methods available to estimate its potential: solar radiation.

In this sense, previous studies show that building and urban form usually result from shaping the building shell without any concern to accommodate the building design program, as the interior configuration and rooms distribution affects the form and the available exterior wall to place the openings.

This paper presents an approach to urban quarter design by using building generative design and performance optimization techniques coupled to dynamic simulation. In the presented approach, the building's design program is the starting point to generate, optimize, and inform the user on the thermal performance of each building block in the urban quarter. This document is made up of four sections. In the first part is presented the problem and its background. In the following section, the methodology is described and the methods presented. In the third section, a showcase is carried out and analyzed. Finally, in the last section, conclusions are made.

2. Methodology

2.1. Generative design technique

The generative technique used in this urban design exercise is an evolutionary strategy enhanced with a stochastic hill climbing method [6–8]. This hybrid population-based approach generates alternative floor plans by allocating spaces and vertical circulations, according to the user's preferences and requirements, defined in the design program. The technique aims to minimize a group of objectives, such as connectivity, adjacency, orientation, lengths and minimum areas, maximum gross and construction areas, overflow of spaces, etc. The approach uses adaptive transformation operators to the individuals according to random geometric actions, such as translation, rotation, reflection, etc. These operators may affect single element, such as an opening or a space, or a cluster of spaces, levels, or the whole floor plan.

The urban quarter is determined by defining suitable depth and width for each building block according to the desired building design program. Alternative building plans are generated and the dimensions are calculated for each block of the O-shaped quarter, made up of 10 buildings. This quarter is surrounded by other buildings with similar height and distanced by 12 meters that correspond to the street. For each building block of the urban quarter, 18 alternative designs are generated and the four fittest designs are used for thermal evaluation and optimization, thus totalizing 40 created buildings. After the thermal performance optimization is carried out to all of these designs, the best performance solution in each building block is chosen. During the generation process and optimization procedure of each building block, the surrounding buildings in the urban quarter are dummy buildings with similar height. In the end of the overall process, the ten best buildings are merged in a single urban design solution.

2.2. Thermal performance optimization

After alternative buildings are generated, the thermal performance is carried out using a sequential variable optimization procedure [9,10]. The building performance is assessed using dynamic simulation (EnergyPlus v8.1.0), which is coupled to the algorithm. All simulation specifications, weather data, constructive system, occupancy and lighting/equipment usage schedules, which for this study are specified in Tables 1 to 3, are set in a database for automatic model formalization. Thus, the thermal performance algorithm changes a set of building geometry variables, besides others. In this approach the variables were the openings position and size, overhang depth, lateral size, and height to the window, and the fins depth. The purpose is to minimize the weighted sum of degree-hours of thermal discomfort in all spaces on the floor plan. The degree-hours are calculated according to the adaptive operative temperature limits for spaces naturally ventilated defined by the European Norm 15251:2007. The sequence of the optimization procedure is according to the user’s design strategy.

3. Showcase

3.1. Building’s design program and specifications

The urban quarter is located in Coimbra, Portugal. It has an O-shape configuration with ten building blocks of three levels. Four streets delimit the urban quarter. Three buildings are placed in the North side and other three in the South side. Every building of the urban quarter has the same design program as specifications. However, the generated designs are different, due to the location of each building in the urban quarter and the exterior openings in the ground floor that must face street side. In the case of the building placed in the Northwest corner, its exterior openings may be oriented North and West. Similarly, the remaining buildings satisfy this requirement. The design program of each building is defined as having three levels. In the ground floor, there is a store and an entrance hall. In the first floor, there are the corridor, the kitchen, the living room, one bedroom, and one bathroom. In the last level, there are three bedrooms and a bathroom. One stair serves all levels.

Besides the building’s geometry, the dynamic simulation was carried out using common constructive and usage specifications of this kind of design program. Table 1 lists the occupancy, schedules of use, activity, and number of occupants in each space. Also, in Table 2 are listed the artificial lighting and equipment in each space. Table 3 depicts the constructive system for each building element and the materials physical properties. Besides these specifications, each space that has an exterior opening with an infiltration rate of 0.4 ACH. If at a specific time, a space is occupied and the temperature difference to the exterior is one degree or superior, a ventilation rate of 1.5 ACH is summed up. The weather data is for Coimbra, available in the US Department of Energy website.

Table 1. People occupancy, activity, and schedule by space.

	Time																									
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	{W}	**Pp**
Hall/Corr. (3x)									▨				▨	▨					▨	▨			▨		190	2
Stair									▨				▨	▨					▨	▨			▨		190	2
Store								▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨						190	2
Kitchen									▨				▨	▨					▨	▨	▨				190	2
Living room														▨						▨	▨	▨	▨		110	5
Bathroom (2x)									▨				▨						▨		▨		▨		207	1
Bedroom (4x)	▨	▨	▨	▨	▨	▨	▨	▨	▨														▨	▨	72	2

Table 2. Lighting/equipment gains and schedule by space.

	Time																								
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	{W/m2}
Hall/Corr. (3x)									▨				▨	▨					▨	▨			▨		7.0
Stair									▨				▨	▨					▨	▨			▨		7.0
Store								▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨						20.0
Kitchen									▨				▨	▨					▨	▨	▨				10.0
Living room														▨						▨	▨	▨	▨		10.0
Bathroom (2x)									▨				▨						▨		▨		▨		7.0
Bedroom (4x)									▨										▨	▨	▨	▨	▨		7.0

Table 3. Materials' physical properties by element.

Element	**U-value**	**Layer**	**T**{cm}	**λ**{W/m-K}	**σ**{kg/m3}	**Sp**{J/kg-K}	**TA**	**SA**	**VA**
Ceiling/Slab	2.60	High weight concrete	20.0	1.73	2242.60	836.80	0.90	0.65	0.65
Exterior door	2.86	Hardwood	3.00	0.20	825.00	2385.00	0.90	0.78	0.78
		Insulation	1.00	0.04	32.00	836.80	0.90	0.50	0.50
		Hardwood	1.00	0.20	825.00	2385.00	0.90	0.78	0.78
Exterior wall	0.43	Plaster	2.00	0.43	1250.00	1088.00	0.90	0.60	0.60
		Dense brick	11.00	1.25	2082.40	920.50	0.90	0.93	0.93
		Insulation	8.00	0.04	32.00	836.80	0.90	0.50	0.50
		Concrete block	15.00	1.73	2242.60	836.80	0.90	0.65	0.65
		Plaster (gypsum)	2.00	0.22	950.00	840.00	0.90	0.60	0.60
Floor	0.45	High weight concrete	20.00	1.73	2242.60	836.80	0.90	0.65	0.65
		Insulation	8.00	0.04	32.00	836.80	0.90	0.50	0.50
		Lime plaster	2.00	0.80	1600.00	840.00	0.90	0.50	0.50
		Hardwood	1.50	0.20	825.00	2385.00	0.90	0.78	0.78
Interior door	1.36	Hardwood	0.50	0.16	720.80	1255.20	0.90	0.78	0.78
		Chipboard	3.00	0.07	430.00	1260.00	0.90	0.78	0.78
		Hardwood	0.50	0.16	720.80	1255.20	0.90	0.78	0.78
Interior wall	2.17	Plaster (gypsum)	2.00	0.22	950.00	840.00	0.90	0.60	0.60
		Concrete block	7.00	1.73	2242.60	836.80	0.90	0.65	0.65
		Plaster (gypsum)	2.00	0.22	950.00	840.00	0.90	0.60	0.60
Roof	0.37	Slag	1.50	1.44	881.00	1673.60	0.90	0.55	0.55
		Felt and membrane	1.00	0.19	1121.30	1673.60	0.90	0.75	0.75
		Dense insulation	10.00	0.04	91.30	836.80	0.90	0.50	0.50
		High weight concrete	20.00	1.73	2242.60	836.80	0.90	0.65	0.65
		Plaster (gypsum)	2.00	0.22	950.00	840.00	0.90	0.60	0.60
Element	**U-value**	**Type**	**SHGC**	**VT**					
Window	2.60	Double Glazed Win.	0.63	0.70					

T - layer thickness; λ - conductivity; σ - density; Sp - specific heat; TA - thermal absorptance;
SA - solar absorptance; VA - visible absorptance; SHGC – solar heat gain coefficient; and VT – visible transmittance.

3.2. Results and Discussion

After generation of the four alternative designs for each building block, the geometry was changed aiming to improve the thermal performance of all solutions. The best solution of each building block is then selected to the final urban quarter design. The results of this showcase are presented in Fig. 1. In it are depicted four views corresponding to four cardinal points (NW, NE, SW, and SE). The buildings' heights vary due to the stair type and its dimensions that resulted in the generation process. It is possible to observe that building blocks facing south have overhangs in the exterior openings that face this orientation. Also, the windows are larger than in the other buildings. It is also noticeable the same result in the middle building in the north side of the urban quarter, as the exterior openings in the upper levels are free to be oriented south.

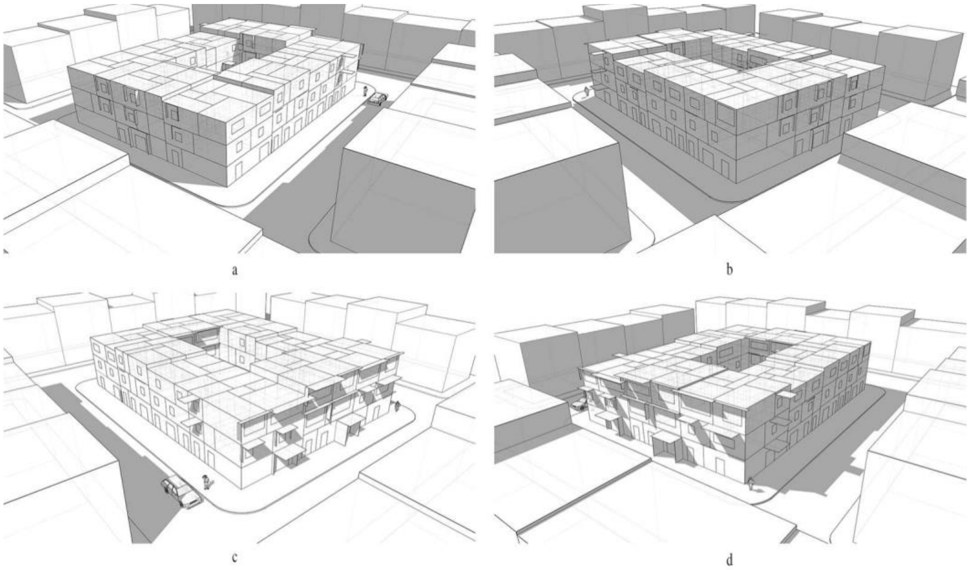
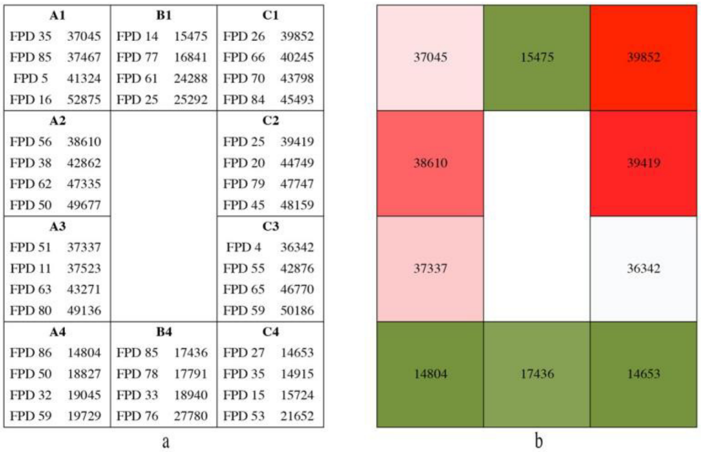


Fig. 1. (a) View from Northwest; (b) view from Northeast; (c) view from Southwest; and (d) view from Southeast.



A1		B1		C1	
FPD 35	37045	FPD 14	15475	FPD 26	39852
FPD 85	37467	FPD 77	16841	FPD 66	40245
FPD 5	41324	FPD 61	24288	FPD 70	43798
FPD 16	52875	FPD 25	25292	FPD 84	45493
A2				**C2**	
FPD 56	38610			FPD 25	39419
FPD 38	42862			FPD 20	44749
FPD 62	47335			FPD 79	47747
FPD 50	49677			FPD 45	48159
A3				**C3**	
FPD 51	37337			FPD 4	36342
FPD 11	37523			FPD 55	42876
FPD 63	43271			FPD 65	46770
FPD 80	49136			FPD 59	50186
A4		**B4**		**C4**	
FPD 86	14804	FPD 85	17436	FPD 27	14653
FPD 50	18827	FPD 78	17791	FPD 35	14915
FPD 32	19045	FPD 33	18940	FPD 15	15724
FPD 59	19729	FPD 76	27780	FPD 53	21652

a

37045	15475	39852
38610		39419
37337		36342
14804	17436	14653

b

Fig. 2. (a) Thermal performance results for the four building designs in each building block (weighted sum of degree-hours); (b) Thermal performance results for each building. Grading green-to-red represents best-to-worst overall building thermal performance. C4 has the best performance and C1 the worst. Top row faces north and bottom row faces south.

Fig. 2 illustrates the thermal performance results for the four alternative designs in two graphics, represented by the weighted sum of degree-hours of thermal discomfort. In the right is represented a schematic of the urban quarter where a color grading, from green-to-red, represents the best-to-worst thermal performance, respectively. It is possible to observe that buildings that have walls with exterior openings facing south have the best performance (green color). The worst performance solutions are placed in the east side of the quarter (red color). Thus, the best building performance solution is placed in C4 (southeast corner of the urban quarter). In the left side of the figure is depicted the sorted performance of the four design solutions in each building block. As it is possible to observe, the results are not just fruit of randomness of design, as the alternative designs have their performance within the same range of values. e.g. building block A1 has the four designs ranging between 37045 and 52875 degree-hours and C4 between 14653 and 21652.

Therefore, if the urban quarter had other configuration, for instance a horizontal O-shape configuration with the major axis oriented to East-West, the number of building blocks with better thermal performance would be greater. Thus, the use of this kind of approaches is very valuable in the urban and architectural design process, not only to generate designs to be further developed in following stages, but also to explore urban configurations that aim to satisfy functional and performance objectives. This approach may be extended to include other decision variables such as for constructive and active systems.

4. Conclusions

In Portugal, Detailed Plans are territorial planning instruments provided by law, which embody the allotment operations [11]. Thus, drawing the lot comes first, subjecting invariably the design of the building to the constraints brought by the prior design of the lot. However, if the thermal performance of the generated solutions are assessed and improved, building practitioners, urban planners or those responsible for the territory planning may take informed decisions, thus avoiding design corrections in future stages of building design. The presented showcase demonstrates that each building performance depends greatly from its position in the urban quarter, and that the shape of the latter is dependent of the satisfaction of the interior arrangements of the design program. Results show that buildings with walls with exterior openings facing south have the best thermal performance by having larger window areas protected by shading mechanisms. This kind of information is very important for practitioners if they aim to design more energy efficient and livable buildings. So, new tools that include performance assessment from the outset are fundamental. Both algorithms used in this case study are now being developed as prototype commercial tool under the project GerAPlanO [12].

Acknowledgements

This work is framed under the *Energy for Sustainability Initiative* of the University of Coimbra (UC) and has been supported by the project *Automatic Generation of Architectural Floor Plans with Energy Optimization* - GerAPlanO - QREN 38922 Project (CENTRO-07-0402-FEDER-038922).

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