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Du, Tiantian; Turrin, Michela; Jansen, Sabine; van den Dobbelsteen, Andy; Bioria, Nimish

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A Review on Automatic Generation of Architectural Space Layouts with Energy Performance Optimization

T. Du ¹, M. Turrin ¹, S. Jansen ¹, A. van den Dobbelsteen ¹, N. Biloría ²

¹Faculty of Architecture and the Built Environment
Delft University of Technology (TU Delft), 2600 AA, the Netherlands

² Faculty of Design, Architecture and Building
University of Technology Sydney (UTS), Broadway, NSW 2007, Australia

SUMMARY

The space layout design is one of the most important phases of the architectural design, and the automatic generation of space layout has shown great potential as a design aid. Research has shown that space layouts can have a significant impact on the improvement of energy performance. The combination of the automatic generation of space layout and the optimization of energy performance is expected to be greatly helpful for the development of an energy efficient design in the early design phase. This paper presents a literature review of the current research about the automatic generation of space layout related to the energy performance.

The following conclusions can be drawn: space layouts have an important impact on the thermal performance of buildings; only several researches have tried to combine automatic generation of space layout with the energy performance optimization; an in-depth investigation into achievements of past researchers on automatic space layout generation integrated with energy performance optimization is thus promising. Besides, these investigations have resulted in outlining several challenges such as: the calculation of the energy performance lacks the integration of different aspects of energy performance; the current automatically generated space layouts lack the flexibility of shapes, and its application in 3D geometry is limited; the generation of space layouts lack the consideration of specific characters of different types of buildings.

KEY WORDS

space layout, automatic generation, computer-aided design, energy performance, optimization design

INTRODUCTION

Architectural space layout design is a stage within the architectural design process that takes place between the "schematic design" phase and the "design development" phase. The space layout design is one of the most important phases of the architectural design, which is relevant to all physical design problems (Michalek et al. 2002). The space layout design is a process to assign relationships to a given function and then a geometry to this function, during which architects translate the client's needs into an architectural programmatic language (Lobos and Donath 2010). Spatial layout is concerned with finding feasible locations and dimensions for a set of interrelated objects that meet all design requirements and maximize design quality regarding design preferences (Michalek et al. 2002).

Different properties of space layout have been researched, including layouts for vision accessibility (Penn and Turner

2003), physical activity (Zimring et al. 2005), occupant behaviour (Goldstein et al. 2011), etc. The Space and Organization Workshop (SPORG) at MIT's School of Architecture and Planning, created in 1990, is explicitly directed towards exploring the interdependence between physical space and organizational behaviour (Horgen 1999). As for the physical performance, Hsu (2000) creates a database with the relationships between spaces and the surrounding (site, sun, light, wind). Space layout, in addition to the common engineering objectives such as cost and aesthetic, is especially concerned with usability qualities and performance (Michalek and Papalambros 2002).

The automatic generation of space layouts uses computational processes to generate designs (Lobos and Donath 2010). There are numerous works focusing on different methods for automatically generated architectural space layouts, and many solutions have been presented and discussed: prototypes, tests, depth computer programming, and optimization formulas embedded in the architectural field (Lobos and Donath 2010). Various studies have been conducted, which show that the automatic generation of space layout has great potential to support architectural design. We especially see potential making buildings net zero energy or energy producing.

The rest of the paper is structured as follows. In section 2, the different methods of automatic generation of space layouts are presented. In section 3, the relationship between space layouts and energy performance is discussed. Section 4 provides conclusions and future research directions to be investigated.

AUTOMATIC GENERATION OF SPACE LAYOUT

Research on the automatic space layout generation started around 50 years ago (Levin 1964). Since then, plenty of studies have been conducted. The outcomes show great potential and serve as inspiration for architects. Kornberger and Clegg (2004) also discussed the relationship between generation and organisational function, which implies that generation will inspire greater possibilities of space layouts, rather than being a passive container. In common, there are basic criteria or constraints that space layouts should satisfy. These can be roughly divided into typology and geometry (Medjdoub and Yannou 2000; Rodrigues et al. 2013b). The geometric constraints include the dimensional requirements for different spaces, like width, length or height. The typological constraints include the adjacencies to different spaces and also to the perimeter of the building, and exterior orientation.

There are numerous works focusing on the problem of automatically identifying optimal architectural layout configurations with different methods. According to the

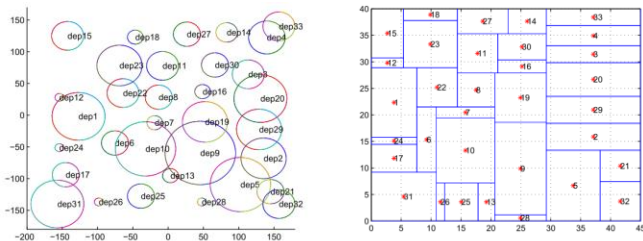
research (Ibrahim 2011), the processes of automatic space layout generation can be divided into generation, search and optimization. The different methods of automatic space layout generation can be grouped within two different categories (Table 1): representation and generation.

Representation of space layout

The representation strategies imply the ways in which shapes and relationships can be represented.

- Coordination-based layout

Spaces are designed based on a coordinate system, with a point for location and width, length or height for dimensions. The adjacencies and connections are represented as constraints, with a cost function for minimization or maximization (Michalek et al. 2002). The constraints are separated into typological and geometric constraints. Mathematical programming methods are used to compute the constraints, like integer programming, nonlinear programming (Jankovits et al. 2011, Fig 1) and mixed integer programming (Ahmadi and Akbari Jokar 2016). Pros: This method separates the constraints definition from the resolution algorithm, which brings a great flexibility in the constraint utilization and is able to incorporate different constraints. It also shows promising capability of application in 3D geometry, with the incorporation of vertical transportation, like elevators and stairs. Cons: This method needs lots of computational effort, and the calculation time increases with the number of constraints and variables.



a. Solution of the first-stage b. Final space layout

Figure 1. Example of space layout for a 30-department (Jankovits et al. 2011)

- Grid-based layout

In this method, a 3D-grid matrix is used to represent spaces and adjacencies, and the building geometry is simplified to be a set of unit cubes with sequential order. The problem of space layout is thus formulated as a binary integer programming (Yi and Yi 2014). Some studies also use the method of “space-filling curve” to define a continuous path to generate spaces on the matrix (Yi 2016) (Fig 2). In the research (Dino 2016), the building form is discretised into a number of equal-area voxels, represented by a 3D matrix (Fig 3). Space layout generation is transformed to match the space with the voxel, thus effectively avoiding the expensive geometric overlap detection. In the study by Guo and Li (2017), spaces are represented by spheres and capsules with point-vector within a 3-D grid matrix. The 3-D space layouts are obtained with the integration of attraction, repulsion, swap and compression behaviours. Pros: This method is time saving and it is easy to develop in 3D. Cons: Mostly, the building geometry needs to be pre-defined and the size of spaces needs to be multiples of a single module.

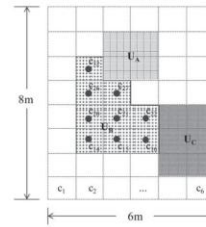


Figure 2. Representation of spaces (Yi 2016).

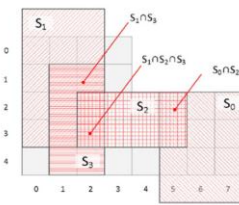


Figure 3. Representation of spaces (Dino 2016)

- Tree data structure representation

Spaces are stored as nodes within a binary tree data structure and another matrix is used to represent the adjacency. This method acquires spaces by repeatedly subdividing a given area in vertical and horizontal directions (Aiello, La Scalia, and Enea 2012) (Koenig and Knecht 2014) (Das et al. 2016). The site space is the root node, and it is divided into two according to the coordinate of the slicing point. All points are located on the right or left branch of the tree, according to the coordinates. The process repeats until all spaces are stored in the tree. In the study by Das et al. (2016), different splitting strategies are developed, e.t. split by distance, split by area, split by line, split to meet minimum dimensions, split by offsetting polyline points (Fig 4). A pathfinding algorithm is employed to find the shortest paths between points in the space. Pros: Each space node contains the data of the neighbouring spaces, which makes it easy to represent the adjacency. Cons: It has not been developed into 3D layouts. Besides, rectangular shapes are needed for both spaces and the boundary of buildings. The characters of final layouts deeply depend on the splitting strategies, which are difficult for architects to understand.

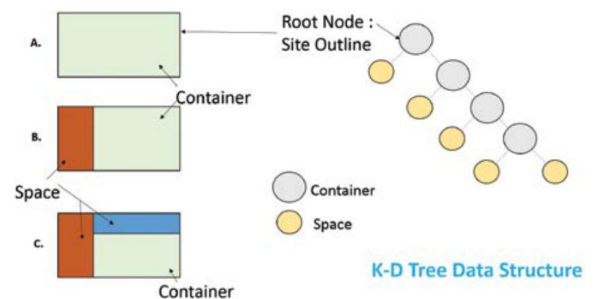


Figure 4. Space data tree construction based on K-d data structure binary tree (Das et al. 2016)

- Graph theory representation

With Graph Theory, spaces and relationships are represented separately by nodes and edges (Lobos 2011). By transforming the information of adjacencies and connections, the graphs are capable of reducing the complexity of buildings. Different algorithms from graph theory are applied to space layout generation. In the study by Lobos and Trebilcock (2014), a schematic space plan is turned into a simplified graph with nodes and edges. Then, the graphs are tuned into XML language and additional information about performance parameters are added to the graph structure. In the research (Hua 2016), space activities and adjacencies are noted in matrix, and regions are detected from raster images and parameter vector graphics

(Fig 5). Then, subgraph matching techniques are used to find the valid mapping from the activities to the detected regions. The Voronoi diagram is another method that is also discussed, which is a set of regions partitioning a plane, where each point is closest to one of several predefined seed points. Chatzikonstantinou (2014) extended the Rectangular Voronoi Diagram, developed by Choi and Kyung (1991), to 3D with a constraint of vertical intersection to avoid overlapping with neighbour spaces. Pros: Combining with the predefined images or segments, the irregular shapes of layouts are easily generated. The generation process is capable of involving designers' intervention. Cons: Most of them are developed based on predefined space layout or a predefined building boundary, which is not suitable for the early design phase.

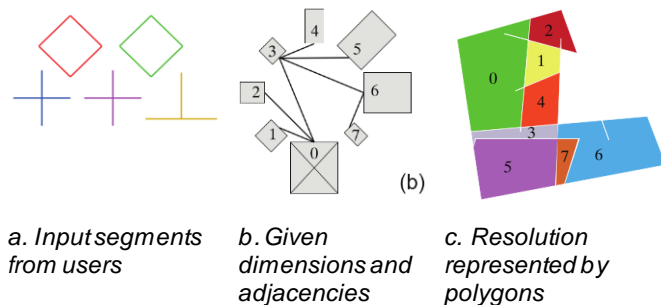


Figure 5. Procedure of space layouts generation (Hua 2016)

Generation of space layout

Depending on the different methods for the representation of space layouts, there are mainly two methods for the generation of final solutions.

- Extend the representation method

Some of the methods of representation can be developed for the generation, satisfying the specific requirements of typology and geometry. It is commonly used in the non-complex problem with limited amount of resolutions. It can be seen in the method of tree data structure that the data structure and slicing algorithm has determined the resolutions of space layouts (Das et al. 2016). Also in the graph theory representation, the designer's intervention is included in the design process and the generation is depended on an independent graphic software. So, no other algorithm is needed for the generation (Lobos and Trebilcock 2014).

- Combine with evolutionary method

With the increase of design variables and constraints, the complexity of the problem is aggravated and the enumerative method is not appropriate. Evolutionary methods have been validated to be efficient in solving complex layout problems. Design variables are selected according to the definition in the representation method, and the typological and geometric requirements are translated or formulated into fitness or objectives. Some of the common evolutionary methods are genetic algorithm (Guo and Li 2017) and simulated annealing (Hua 2016; Yi 2016). In some studies, the generation of space layouts is divided into different stages, with different suitable optimization algorithms. The combination of different evolutionary algorithms is also explored, like Evolutionary strategy with Simulated Annealing

(Rodrigues et al. 2013b) and Simulated Annealing & Genetic Algorithm (Michalek et al. 2002).

CONCLUSION

In conclusion, different methods and tools have been explored for the automatic generation of space layouts. Nevertheless, no applicable tool has been broadly used in architectural design. Besides, the current methods of automatic space layout generation are mostly limited to 2D applications, and only a handful of studies have explored 3D applications. Most of the explorations of architectural automatic space layout generation are developed from the research of automatic facility layout generation, which lack the consideration of different functions of building spaces, as well as the typologies of different types of buildings.

Table1. references of different methods of automatic space layout generation

Author	Year	Representation	Model	Optimization
Jankovits et al.	2011	Circles within coordination	Multi-stage Mathematical programming	Semidefinite optimization
Ahmadi & Jokar	2016	Circles within coordination	3-stage Mathematical programming	convex optimization
Rodrigues et al.	2013	Rectangles within coordination	Mathematical model	Evolutionary strategy & SA
Michalek et al.	2002	Rectangle within coordination	Mathematical geometry	SA & GA
Medjdoub & Yannou	2000	Rectangles within coordination	Mathematical model	exhaustive enumeration;
Yi & Yi	2014	3D Grid Matrix	binary integer programming	SA
Yi	2016	3D Grid matrix	Space-filling curve	SA
Dino	2016	3D Grid matrix	Match the space with the voxel	Evolutionary optimization
Guo & Li	2017	3-D grid matrix	Integration of attraction, repulsion, swap, compression	GA
Das et al.	2016	tree data structure	K-d tree algorithm	-
Aiello et al	2012	tree data structure	Guillotine cut	GA
Koenig & Knecht	2014	tree data structure	Defined rules of subdivision	GA
Chatzikonstantinou	2014	Rectangle	Rectangular Voronoi Diagram	NSGA-II
Lobos & Trebilcock	2014	Nodes, edges,	Graph theory - yED	-
Hua	2016	regions for location;	detection algorithms	SA

SA: Simulated Annealing; GA: Genetic Algorithm

RELATIONSHIP BETWEEN SPACE LAYOUT AND ENERGY PERFORMANCE

Research on the impact of space layouts on building's energy performance has been conducted for decades. Here, the energy performance can be divided into thermal performance (for heating and cooling demand), daylight performance and ventilation, all aspects having impact on the energy use of a building. Plenty of studies have shown the importance of space layout for the improvement of different aspects of energy performance. But, most of the current studies are related to the thermal performance. There are also some studies about the thermal zoning strategies, which can also imply the impact of space layouts. Besides, the current exploration about how to combine the automatic generation of space layout with energy performance optimization is also presented.

Space layouts' impact on thermal performance

Musau and Steemers (2008) investigated the impact of different office space layouts on the energy demands for heating, cooling, and lighting. In the calculation, the influence of daylighting and natural ventilation on the thermal loads is considered. It explored typical UK office layouts, with different utilisation densities and intensities. The combined thermal and lighting loads vary 19% in peak winter, and 51% in peak summer. Since occupancy rates are regarded, the variation is also given per capita or user in the building. Per capita, the combined thermal and lighting loads vary 16% in peak winter, and 80% in peak summer. This phenomenon is also demonstrated in their research with laboratory buildings (Musau and Steemers 2007). They tested the difference between open, closed and mixed layouts, and also 5 different closed space layouts. The test result shows that the winter loads vary 40%, and 50% in summer. In the study of Rodrigues et al. (2013a), the different space layouts, which are generated with same requirements, are sorted according to the thermal discomfort. The factor is a weighted sum of differences between the interior hourly air temperature in each space and the operative comfort temperature limit. The result shows that the difference between the best and worst thermal performance reach up to 17% for the single-level house and 35% for the two-level house. These studies demonstrate that space layouts have significant impacts on thermal and lighting demands.

Zoning strategies' impact on thermal behaviour

Beside the general impact of space layout on the energy performance, there are also some studies about the zoning strategies' impact on thermal behaviour. The thermal zone is a single space or a collection of indoor spaces whose desired thermal conditions are similar (ASHRAE 2016). As they have the similar position in the design process, the combination of space layout and thermal zone benefits higher degree of improvement of final energy performance (Yi 2016). The research of zoning strategies' impact on thermal behaviour also hints the impact of space layouts.

Most current research on zoning is about the energy prediction in the software, which shows that the energy consumption may be quite different with different zoning strategies (O'Brien et al. 2011 ; Harrou et al. 2016). Bleil de Souza and Alsaadani (2012) explored the relationship between different zone divisions and the prediction of annual

energy demands for heating and cooling in office buildings, and they tested three different zoning strategies: a 'single zone' model, a '5 zone' model, and an 'office in use' model. Although the paper doesn't provide more details about the setting of simulation like the temperature for different zones, the result shows that different zoning strategies impact the energy demands with significant variations, from 5.59 kWh/m² to 11.69 kWh/m² for heating and from 28.04 kWh/m² to 37.06 kWh/m² for cooling. Dogan et al. (2014) tested the impact of the internal-zone heat flows on the internal loads, with a perimeter and core subdivision with different inter-zonal heat and mass transfer scenarios, by adding conduction, solar radiation and different levels of air mixing step by step to the adiabatic interior zone boundaries. The result shows that the differences of heating and cooling demands vary from 3.6% to 41% for heating and from 2.2% to 10.4% for cooling. In the study by Yi (2016), the result shows that the annual heating and cooling loads of different thermal zone configurations varies from 50 kWh/m² to 72 kWh/m².

Automatic generation with energy performance optimization

Space layouts have a great impact on the building's energy performance as indicated. There is limited research about the combination of automatic generation of space layouts with energy performance (Table 2). Rodrigues et al. (2014) explored how to improve the thermal performance of the automatically generated space layout, with an optimization algorithm (Fig 6). The thermal performance is calculated in the method of dynamic simulation with EnergyPlus. The design variables are floor plan orientation, window orientation and size, overhang size, fin size, and wall translation. Yi (2016) developed a method of optimal thermal and spatial zoning integrating the building thermal performance simulation, with a simulated annealing algorithm (Fig 7). The criteria are annual energy use intensity (including heating and cooling loads), PMV (Predicted Mean Vote), indoor daylight level, interior shading. But, as for the calculation of energy use for heating and cooling, the method is an approximation of heat balance-based analysis with Ecotect, which lacks accuracy. Michalek et al. (2002) explored the automatic generation of space layout, satisfying the criteria of minimal heating (monthly) and cooling (monthly) loss, minimal lighting (hourly) cost, etc, in which, the calculation was based on simple mathematical functions. The combination of feasible sequential quadratic programming and simulated annealing is used for optimization.



Figure 6. Examples of the generated layouts (Rodrigues et al. 2014)

- The evaluation should include the integration of different aspects of energy performance.

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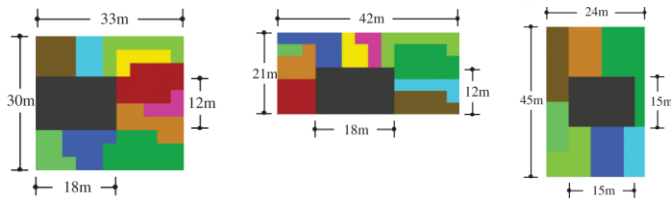


Figure 7. Samples of layouts generated (Yi 2016)

The studies have shown that space layouts have great potential to improve the energy performance and the combination of space layout and energy performance has shown promising solutions. Several challenges are highlighted: time consumption for simulation is the common problem met with these researches; the shapes of geometry are based on rectangles and lack flexibility, compared with the real design projects; only thermal performance is included and sometimes calculated in a very simplified way; the evaluation criteria are separately decided, which makes it difficult to compare the different studies.

Table 2. researches on automatic space layout generation with energy performance optimization

Authors	Constant parameters	Design variables	Energy performance
Rodrigues et al., 2014	-occupancy schedule	-dimensions - adjacent buildings - gross area - orientation - openings - preferable space location	-thermal discomfort (a sum of differences between the interior air temperature and the operative comfort temperature)
Yi, 2016	-boundary	-building perimeter -core -internal space occupancy - fenestration	-annual heating and cooling loads - PMV - indoor day light level
Michalek et al., 2002	-boundary	- space location - distance to wall - size of windows	- day lighting: horizontal illuminance - heating loads - cooling loads

CONCLUSION

A comprehensive survey associated with automatic space layout generation with energy performance optimization is presented in this paper. With this study, several conclusions are obtained. The automatic generation of space layout is a great aid for architectural design; space layouts can improve the energy performance significantly; the combination of automatic space layout generation with energy performance optimization is promising; but there is only limited research aiming at the combination. More future research is needed, and several directions that should be following are suggested here:

- The geometry of building should have higher flexibility in both 2D and 3D;
- The space layout should include different characteristics of different types of buildings;
- The time consumption for simulation and generation should be less;

- with Graphical Inputs." *Automation in Construction* 72:388–96.
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