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Research paper

Multi-objective optimization of the floor plan of a single story family house considering position and orientation

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ABSTRACT

Improving the architectural layout for diverse objectives using rigorous mathematical optimization methods gradually receives more attention by the researchers. Such optimization however, is usually reduced to a much simpler and relatively well-defined problem such as: facility layout optimization, quadratic assignment problem, rectangle partitioning. Nonetheless, architects are usually skeptical about such approaches since they produce solutions which lack certain architectural qualities.

This paper proposes a framework where architectural functional layout (FL) is optimized for the following objectives: functionality (defined by users), insolation (calculated according to geographical conditions), outside view attractiveness (assessed on-site) and external noise (measured on-site). Incorporating the latter two and simultaneous optimization of FLs for objectives related specifically to the site: position and orientation are the novel contributions of this paper. Firstly, a set of candidate FLs is generated, next they are evaluated for optimal location and orientation on a given site. Optimality is conceived here as maximization of real-valued objective function combining: user's satisfaction level of the outside views, shielding from external noise, and insolation preference. The importance of these factors for each type of room is assessed by the user (as weights).

A case study on an existing site is presented. The view quality was arbitrarily assessed and the noise map was assessed by A-weighted equivalent sound level measurements.

A general gradient-based method for finding optimal and near-optimal solutions was applied. The output of this optimization is a set of room configurations with their locations and orientations on the site returned to the user for final selection.

1. Introduction

Architectural design is particularly difficult because it must combine a variety of engineering problems with other types of challenges, such as aesthetic and psychological issues which are usually ill-defined and arbitrary. Architecture is particularly hard to model since it requires the inclusion of unusual factors (such as aesthetics, cultural background, symbolism, etc.) [1]. Among all engineering disciplines in the field of architecture, communication is the closest to the natural language as it includes emotional statements (e.g. ”it is beautiful“) and personal judgments (such as ”I like it“). Thus it can easily generate contradictions and paradoxes [2]. According to Ref. [3] the term *architecture* can be defined in over two thousand ways, which alone indicates the complexity of the problem.

Single-family house (SFH) is an archetypal architectural problem. Not only because it deals with the creation of a habitat for the basic social unit – family, but it also represents the entire spectrum of issues pertaining to architecture. Since the scale of this classic problem is relatively small, it is usually manageable by an individual architect. The architectural design contexts (natural, symbolical, ideological, etc.) are relatively diverse and inspire architects' imaginations. This makes SFH probably the most favored type of design among architects. It is also worth mentioning, that according to Ref. [4] the designing process is usually pleasurable for a designer, and the satisfaction seems to be proportional to the difficulty of the intellectual effort. It is fundamental for mankind, as biologists believe that the pleasure associated with solving difficult mental, social, or intellectual problems may represent mechanisms by which human genes have built human brains so as to favor problem solving [5]. Design, in particular - architectural design is a ”multifaceted“ intellectual challenge, which can be considered as an optimization problem, as soon as the optimization objectives are mathematically formulated. Many of architectural criteria are difficult to assess unequivocally. On the other hand, the need for building dwellings is as old as humanity. Thus architecture has developed its

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own methods for solving design problems, and the introduction of formal optimization techniques is gradual and started with the advent of computation in1930′s [6–8]. For review of the use of examples for automating architectural design tasks see [9]. The importance of close collaboration between architecture and engineering is discussed in [10]. The authors propose there a structural topology optimization framework which can potentially integrate both communities. *Truss-Z* modular system is an example where structural and topological optimization of the geometry of the base module, optimization of the entire construction and architectural form & function are inseparable [11–13].

Architectural layout design is a fundamental, nevertheless - only a part of architectural design. Applications of rigorous mathematical optimization methods for improving architectural layouts have been studied for several decades. Such optimizations, however, are based on reductions to much simpler and relatively well-defined problems:

- Facility layout optimization is a problem where the layout geometry is given and only the arrangement of facilities is to be optimized. Heuristic methods such as genetic algorithms [14], simulated annealing [15], annealed neural network [16] and tabu search strategies (including multi-searching tabu search strategy) [17] have been successfully implemented for this kind of optimization. More recently, several methods for unequal area facility layout problem have been proposed: a genetic algorithm-based methodology for handling its qualitative aspects [18], implementation of ant colony optimization has been documented in [19], application of simulated annealing and biased random-key genetic algorithm have been demonstrated in [20,21], and [22], respectively.
- Quadratic assignment problem has been formulated by Armou and Buffa in 1963 as assigning facilities to given shapes on grid. Their work resulted in a computer program CRAFT (computerized relative allocation of facilities technique) [23] followed by successful implementations of evolutionary algorithms [24,25]. For more recent investigations on evolutionary strategy enhanced with a local search technique for the space allocation problem in architecture see [26,27].
- For the layout optimization simplified to rectangle partitioning, a number of programs based on constraint satisfaction have been implemented in the past: LOOS/ABLOOS [28], SEED [29], HeGeL [30] and WRIGHT [31].

The results of these approaches, however, are rarely accepted without substantial manual modifications by designers since they usually lack certain organizational, aesthetic, or identifiable characteristics [32]. An alternative method based on coarse grid and implementation of architectural expertise which produces more realistic layouts from designer's perspective has been presented in [33]. In that paper a three-objective constrained minimization of: the overall geometrical complexity of the layout, the corridor size, and distance of certain room from given position has been presented. Constraints were given to the lot size and distances between selected pairs of rooms within apartments. For preliminary results of generating spatial architecture in 3D grid by an agent-based topology finding system see [34].

In the presented work, the problem of single story SFH layout design is approached as a multicriterial optimization where certain objectives are to be minimized (the internal communication area, noise exposure) and others are to be maximized (functionality, direct sunlight exposition of certain rooms, outside view quality). For overview of thermal, luminous and sonic environments in the context of architectural design see [35]. The importance of the following occupant needs: thermal comfort, air quality, acoustic comfort, visual comfort, room layout, energy use, influence on indoor climate, fire protection, health & environment, vibration protection, and accessibility have been investigated in [36] by surveying 1416 occupants of residential buildings.

The architectural form-finding by these criteria (or their combinations) resulted in development of several building performance-oriented methods. Most of the studies described in literature focus on the energy performance for heating, cooling, and lighting in buildings. Ref. [37] presents a three-objective optimization of the window parameters to determine trade-off design solutions between: energy consumption, indoor thermal environment and visual performance. For reviews of computational optimization methods applied to low-energy (sustainable) building design see [38,39]. For a review of existing literature of methods in measuring light-induced physiological responses to perceived glare in office buildings see [40].

Regarding thermal comfort, a multilevel engineering design optimization framework to the problem of thermal and HVAC optimization of three building units has been presented in [41]. Draft comfort in a slot-ventilated room at various inlet aspect ratios has been investigated in [42].

Regarding relevant luminous environment-oriented literature, a genetic algorithm-based method for fenestration size optimization in two locations: Phoenix, AZ (cooling-dominated situation) and Chicago, IL (heating-dominated climate) has been presented in [43]. "Human-guided optimization" of natural light illumination performance in the building interior has been presented in [44]. Ref. [45] demonstrated how elevation of a building can be designed as a function of interior lighting requirements. A later paper [46] presented agent-based genetic algorithm optimizing access to direct sunlight for a set of high-rise buildings. A recent paper [47] presented two-objective optimization of a high-rise building for: indoor daylight distribution and aesthetic perception of the building envelope.

According to Refs. [48,49], environmental noise, such as transportation noise in residential areas, is the main factor causing annoyance, and rest, sleep, cognition, and communication disturbances. The relationship between noise exposure and annoyance or sleep disturbances have been investigated in multiple studies [50–55]. Moreover, epidemiological studies have demonstrated that transportation noise is associated with blood pressure and hypertension. Ref.[56] investigated the effects of transportation noise exposure on blood pressure in 400 adult residents of multi-story residential buildings and modifying effects of indoor noise annoyance and self-rated noise sensitivity on the associations between transportation noise and blood pressure. The effect of building facade on indoor transportation noise annoyance in terms of frequency spectrum and expectation for sound insulation has been studied in [57]. The models of perceived oppressiveness and noise annoyance responses to window views of densely packed residential high-rise environments have been presented in [58].

As mentioned above, architectural design is a complex task. There are usually a number of antagonistic criteria (e.g.: size, price, function, etc.) and various constraints (e.g.: legal, technological, aesthetic, economical, etc.) to be considered. In practice, design team strives to counterbalance these criteria without violating imposed constraints. Usually performance simulation tools are employed mainly as a decision aid. For a review of the methods and tools used for the building design optimization in an effort to explore the reasoning behind their selection see [59]. For an extensive benchmark of global search algorithms in building energy optimization see [60]. Many building optimization studies to date have used simple hypothetical buildings. For effective building performance optimization of: building energy efficiency and indoor thermal comfort applied to the design of a newly built complex building see [61]. An algorithm for two-objective optimization of the building envelope of single family houses considering: construction cost and energy performance has been presented in [62].

Some aspects of design considered in our work have discrete nature such as the functional relationships between rooms, while others are continuous, e.g. insolation and noise abatement. Most importantly, some of the criteria are relatively straightforward (such as insolation), some are relatively complex (e.g. acoustic environment of the building plot) and some are purely arbitrary, based on the individual's judgment, e.g. the quality of the outside view).

This paper presents preliminary results of the multidisciplinary task of designing a single story SFH floor plan. From the computational prospective, our method is divided into two distinct phases which differ fundamentally regarding applied algorithms and their implementations:

1. Phase 1: Generation of functional layouts;
2. Phase 2: Evaluation of the layouts in a given scenario.

In the phase 1, a graph-theoretic combinatorial search returns a set of candidate architectural functional layouts (FL) which meet a number of user-defined (practical) conditions. Each FL can be represented as a graph, where adjacent nodes correspond to the neighbouring rooms. These graphs are constructed by a depth-first backtracking search algorithm which, in principle, can generate all possible planar, connected room configurations. However, the search is significantly ”narrowed“ by pruning configurations which violate any given constraints (spatial, functional, and others). For more details on this procedure see Section 2 and the reference article [33] which is entirely focused on this subject.

A set of FLs was generated by an algorithm implemented in *Mathematica* and parallelized on a computer cluster. Generation of the entire set of FL for the case discussed in Section 2, depending on the input data takes from a couple of hours to a couple of days. Computational cost required to generate candidate FL depends on: the maximal number of rooms, their sizes & shapes, and imposed constraints. In the second phase, the output of the FL generator is evaluated. In order to calculate the value of the objective function, a proper characterization of environment is necessary. These characteristics are provided as quantified user preferences. Optimization is performed with a dedicated program written in Python (with SciPy), based on a gradient method for finding the extreme of the objective function. In order to guarantee that the global optimum is found, a large number of initial conditions is densely distributed in the search space. The entire problem is essentially three-dimensional: two variables for the location of a FL on the building plot and the third being its azimuth. It can be solved by a modern desktop computer in a matter of minutes for each FL. Details of the numerical formulation are presented in Section 4.

In summary, the novel contributions of this paper are:

- Four-objective optimization for the following criteria:
  - Layout functionality;
  - Insolation of selected rooms;
  - Outside view attractiveness for selected rooms;
  - External noise shielding of selected rooms.
- Simultaneous optimization of the single family house layout, its position and orientation on the given site.
- Inclusion of noise heat-map of the building site for internal arrangement of rooms in the layout.
- Inclusion of subjective aesthetic impression as one of the optimization criteria, namely the quality of the outside view.

1.1. Single family house

The general objectives and constraints considered here for the design of a single family house (SFH) formulated as a multicriterial optimization problem are listed in Table 1

The construction of a building is based upon a detailed architectural document (so called “blueprint”), which is an elaborated form of a properly designed functional layout (FL). According to Ref. [33], FL represents graphically the relationships among the parts of a building with assigned functions. Although the levels of accuracy can vary, the sizes and dimensions of spaces need to be represented with proper proportions, so the elements of a functional layout roughly correspond to the final architectural plan (blueprint). The relationships between FL, blueprint and the (virtual or real) building are illustrated in Fig. 1.

In this paper, the architectural aspects of single story SFH are limited to its FL. This is obviously a major simplification, since the technicalities collected in documentation required for erecting any habitable engineering construction are usually very complex. However, here this simplification is reasonable since we focus here on the initial stage of architectural design, also called the conceptual design.

2. Phase 1: Generation of the set of candidate functional layouts

This phase of the procedure is based on the constrained satisfaction approach introduced in [33]. The method is based on the observation that – although in theory, rooms in a floor plan can have any sizes and proportions [63] – the proportions and sizes of such rooms lie within surprisingly narrow ranges. In fact, the proportions of a typical room in a residential building lie between a square and two squares. The proportions of rooms have been the subject of geometrical study for centuries. One of the most prominent architects concerned with this issue was Andrea Palladio (A.D. 1508 – 1580) who translated philosophical Pythagorean concepts of proportions to terms useful to any architect. In Book I Chapter 21 of *I Quattro libri dell'Architettura* [64], he listed seven best shapes for room plans: round, square, or rectangular with a length/width ratio of: $\frac{4}{3}$, $\frac{\sqrt{2}}{1}$, $\frac{3}{2}$, $\frac{5}{3}$ or $\frac{2}{1}$, as illustrated in 2. He also advised to avoid exceeding the length/width ratio of $\frac{2}{1}$.

For a comprehensive study of proportions used by Palladio in architectural design see [65]. Recently, an alternative approach for determining the dimensional ratios of rectangular rooms based on acoustic properties has been presented in [66], where the optimal dimension ratios depend on the room volume and the sound damping inside a room. For small and medium volumes the best width/length/height ratios are approximately: 1/1.48/2.12, 1/1.4/1.89 and 1/1.2/1.45. For large room volumes this ratio is 1/1.2/1.44.

According to Ref. [33]: i. functional layouts (FL) can be solved in discrete space, ii. any FL can be transformed into an architectural floor plan, iii. for a given type of FL, the number of size variations of rooms is relatively small, and iv. combinatorial search is feasible in functional design space.

Most architectural layouts are based on some kind of a grid system. Moreover, a relatively new research field devoted to study human crowd dynamics by means of transition probabilities [67–70]. Such simulations use rule-based models with quantified time and space discretized in regular grids.

There are three regular grid systems based on, so called, ‘Platonic’ tessellations. The practical use of square, hexagonal and triangular grids in architectural and urban design and crowd simulations are: extremely common, relatively rare and very rare, respectively. ‘Platonic’ tessellations divide Euclidean planar space into congruent units of the same shape and surface area. The symmetry group of regular tilings is transitive on the tiles. They are homogeneous with respect

Table 1
Selected optimization criteria for designing a SFH. The objectives can be contradicting and are subject to the following constraints: functional relationships among spaces; architectonic requirements (room sizes and shapes, structural dimensions, etc.), and the building plot conditions.

Criterion	Objective	Constraints
Noise exposure	Minimize for spaces requiring silence	Functional relationships among spaces
Exposition to attractive view	Maximize for rooms expected to posses a nice view	Architectonic requirements (room sizes and shapes, structural dimensions, etc.)
Daylight / sun-heating	Exposition highly depends on functional properties of rooms	Site conditions

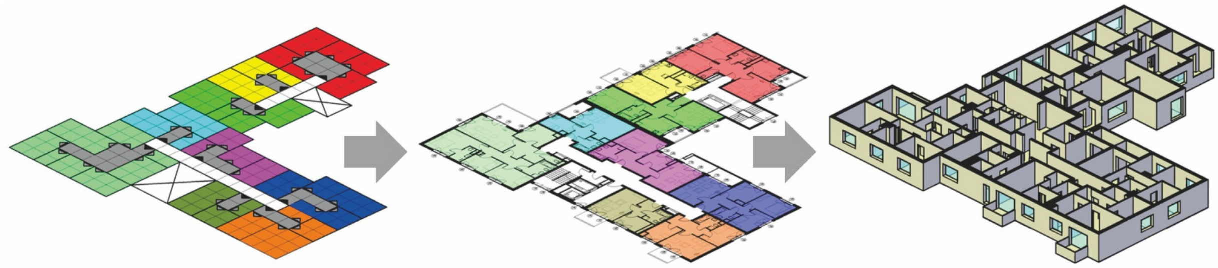

Fig. 1. Three stages of any architectural design shown schematically. From the left: functional layout, architectural blueprint, and the (virtual) building.

to vertexes, tiles and edges and are strongly edge-homogeneous [71]. This is equivalent to an edge-to-edge tiling by congruent regular polygons. The use of this property has a long history in various kinds of design. In the early seventeenth century, Kepler gave it the first rigorous mathematical consideration in [72]. For discussion on the use of regular tessellations in design see [73].

As mentioned above, square grid is a common quantification of space used in crowd simulations. The empirical maximum density of a human crowd is 6.25 persons/ m^2 [74]. Thus the minimum space required for a person is 0.16 m^2. This is equivalent to a $40 \times 40\,cm^2$ square cell in a grid. This is the common size of an agent usually assumed in crowd simulations of pedestrians in discrete models [75]. In the case of generating optimal FLs the grid is larger as it relates to architectural functional requirements and equals to approximately 1.5×1.5 m cells, as shown in Fig. 3. This value corresponds to the width of a minimal internal corridor.

Ref. [76] introduced a user-friendly platform for simple crowd simulations on any floor plans. A straightforward but robust and flexible agent-based system is used there for modeling of crowd dynamics. Such simulations can be performed at any stage of design, which can be particularly useful at the conceptual phase.

In the presented work, the candidate FLs are generated in the first phase, according to the procedure described in [33], that is:

1. The user's input of the layout-related preferences:
   (a) the list of rooms with lists of their acceptable and preferred sizes
   (b) the size and shape of the allowable building footprint
   (c) the preferences regarding internal relationships, e.g.: 'Kitchen to be adjacent to the Living Room', 'Pantry to be not farther from the Kitchen than one grid cell', etc.
2. The user's input of the site-related preferences:
   (a) insolation at different times of a day
   (b) outside view quality for each room
   (c) the importance of external noise for each room.
3. A set of implicit constraints to be explicitly defined, e.g.:
   (a) some constraints such as room-to-room overlapping and room-out-of-the-building-footprint prohibitions are obvious and straightforward to implement
   (b) some constraints such as arrangement of the rooms so that each can be accessed by a reasonably sized corridor are not obvious and require special pruning functions.
4. Generation of the potential solutions: a depth-first backtracking search algorithm is applied for this Constraint Satisfaction Problem (CSP). During this search, only the complete configurations are collected. Consequently, each room configuration must not violate any constraint and must include all the required rooms. From the designer's perspective it is favorable to have a choice among a number of solutions instead of receiving a single mathematically optimal layout [16]. In this case, 30 solutions have been generated and saved for the second phase, as shown in Fig. 4. The search algorithm has been implemented in *Mathematica* and parallelized on a computer cluster Grafen with 32 cores available in our institution. These computations took approximately 8 hours.Table 2 shows an

example of the initial data provided by a user for a 'balanced' preference profile. In this case the values are set to balance daylight, view quality and noise exposure. In the Appendix, Tables 3 and 4 show the analogous input for view-quality and external noise protection-oriented preference profiles, respectively. The importance has been accessed in the scale from -3 to 3, corresponding to: extremely undesirable and extremely desirable, respectively. "Morining", "Noon" and "Evening" correspond to the time of a day when direct sunlight is desired/undesired for given rooms. "View" corresponds to the importance of the outside view quality. "Noise" sets the importance of noise shielding, where -3 and 3 stand for: "to be extremely well protected from noise", and "external noise is desired", respectively.

3. Properties of the building plot

Fig. 5 shows the building plot for the single story SFH with indicated eight points (A, B,... H) for the field measurements of the noise and view attractiveness evaluation. The latter is assessed in eight directions (1, 2,... 8).

3.1. Assessment of attractiveness of views on the building plot

In most cultures, windows are not used only as apertures in building envelopes admitting natural light. They also provide visual contact with the outside [73]. Visual landscape is important not only due to its aesthetic quality, but since it influences the emotional state of an occupant, it also affects psychological well-being [77]. Thus, according to Ref. [78], the outside view should be given explicit attention in planning and design decisions. The positive effect of natural scenery on the restorative process of surgical patients has been demonstrated [79]. Studies on view attractiveness indicate that views incorporating the sky and horizon are the most appealing to the human eye, especially after dark [80]. Ref. [81] identifies two fundamentally different approaches of quantification of the quality of landscape:

- *Physical paradigm*:
  - landscape quality is an intrinsic physical attribute
  - assessed by applying criteria to landscape
  - subjectivity presented as objectivity.
- *Psychological paradigm*:
  - landscape quality derives from the eyes of the observer

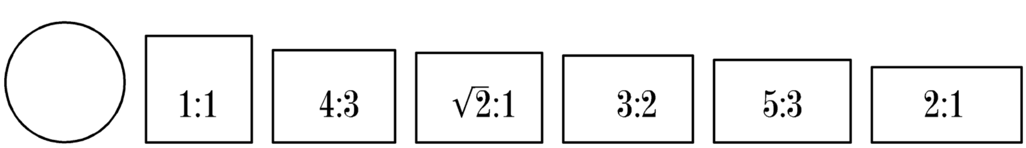

Fig. 2. Seven shapes recommended by Palladio for room plans. From the left: circle and rectangles with increasing base-to-height ratios. All shapes have the same surface area.

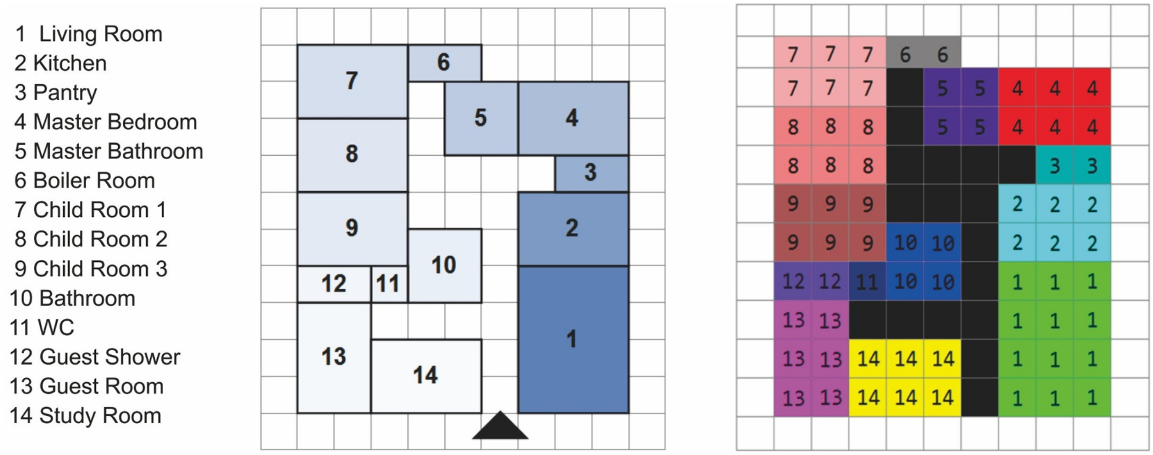

Fig. 3. Example of a functional layout (FL) of a single story single-family house (SFH). On the left: the list of rooms. In the middle: FL on a coarse grid of approximately 1.5 × 1.5 m cells. The black triangle indicates the entrance. On the right: a matrix representation of this FL. Black indicates the corridor. The color convention is used throughout this paper.

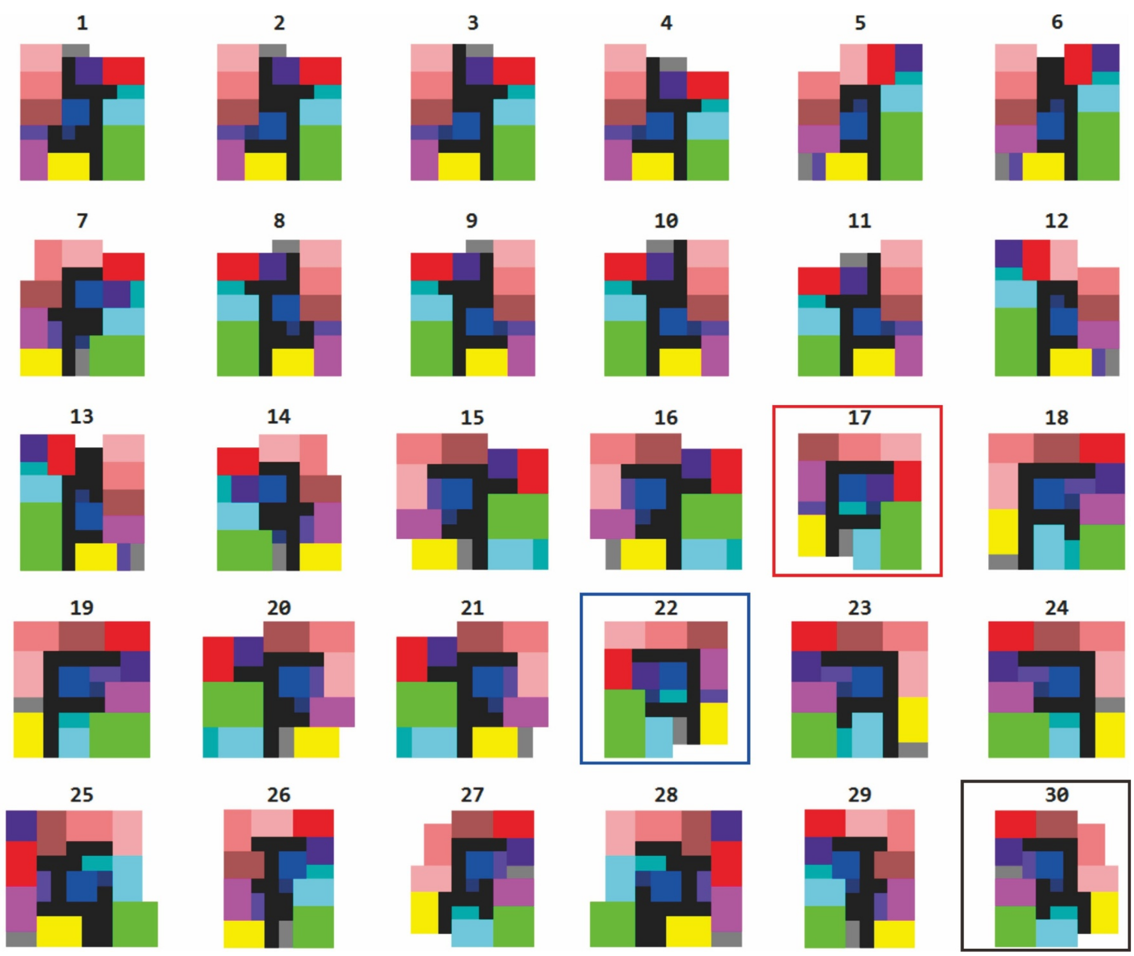

Fig. 4. 30 'good' floor plans meeting all the layout-related preferences provided in Table 2 (as well as Tables 3 & 4 in the Appendix). Three best FLs for: 'view', 'noise', and 'balanced' preference-profile are framed in: blue, red and black, respectively (explained further in text).

- assessed using psycho-physical method
- objective evaluation of subjectivity.

A recent example of the *physical paradigm* has been presented in Ref. [82], where the quality of urban squares has been evaluated upon three normalized properties derived from their plans: smallness, enclosure, and regularity. In that approach, the aesthetics of the detail of urban squares was neglected. It was assumed that the geometrical properties of an urban square as a whole can be clearly understood by any observer. Some researchers claim that aesthetics is fundamental to successful urban design, as it is a more important consideration than legibility [83]. Ref. [84] also points out that visual perception, from the aspect of subjective presentation of objective reality, is an important component in the process of research and development of the physical

Table 2
Balanced: An example of a set of rooms with acceptable sizes and weights reflecting the importance of user-defined preferences. Here the values are set to balance daylight, view quality and noise exposure. Gray background indicates the site-related preferences. “Morning”, “Noon” and “Evening” refer to the times of a day for insolation.

Index	Room name	Morning	Noon	Evening	View	Noise	{width, height}
1	Living Room	1	2	0	2	-2	{{3, 3}, {3, 4}, {3, 5}, {4, 4}}
2	Kitchen	1	-1	-1	1	0	{{2, 2}, {3, 2}}
3	Pantry	0	0	0	0	1	{{2, 1}}
4	Master Bedroom	2	0	-1	2	-2	{{2, 2}, {3, 2}}
5	Master Bathroom	1	0	0	0	0	{{2, 2}}
6	Boiler Room	0	0	0	0	2	{{2, 1}}
7	Child Room 1	2	1	-1	1	-1	{{2, 3}}
8	Child Room 2	2	1	-1	1	-1	{{2, 3}}
9	Child Room 3	2	1	-2	1	-1	{{2, 3}}
10	Bathroom	0	0	0	0	2	{{2, 2}}
11	WC	0	0	0	0	2	{{1, 1}}
12	Guest Shower	0	0	0	0	2	{{2, 1}}
13	Guest Room	0	0	-1	0	-1	{{2, 3}}
14	Study Room	2	1	-2	1	-2	{{2, 3}}

Table 3
View: An example of a set of rooms with acceptable sizes and weights reflecting the importance of user-defined preferences with the highest importance for the quality of the outside-view. Thus this preference profile is called “view”. Gray background indicates the site-related preferences.

Index	Room name	Morning	Noon	Evening	View	Noise	{width, height}
1	Living Room	1	2	0	3	-2	{{3, 3}, {3, 4}, {3, 5}, {4, 4}}
2	Kitchen	1	-1	-1	3	0	{{2, 2}, {3, 2}}
3	Pantry	0	0	0	0	1	{{2, 1}}
4	Master Bedroom	2	0	-1	3	-2	{{2, 2}, {3, 2}}
5	Master Bathroom	1	0	0	-1	0	{{2, 2}}
6	Boiler Room	0	0	0	0	2	{{2, 1}}
7	Child Room 1	2	1	-1	2	-1	{{2, 3}}
8	Child Room 2	2	1	-1	2	-1	{{2, 3}}
9	Child Room 3	2	1	-2	2	-1	{{2, 3}}
10	Bathroom	0	0	0	0	2	{{2, 2}}
11	WC	0	0	0	0	2	{{1, 1}}
12	Guest Shower	0	0	0	0	2	{{2, 1}}
13	Guest Room	0	0	-1	0	-1	{{2, 3}}
14	Study Room	2	1	-2	0	-2	{{2, 3}}

Table 4
Noise: An example of a set of rooms with acceptable sizes and weights reflecting the importance of user-defined preferences with the highest importance for the protection from the external noise in certain rooms. Thus this preference profile is called “noise”. Gray background indicates the site-related preferences.

Index	Room name	Morning	Noon	Evening	View	Noise	{width, height}
1	Living Room	1	2	0	2	0	{{3, 3}, {3, 4}, {3, 5}, {4, 4}}
2	Kitchen	1	-1	-1	1	0	{{2, 2}, {3, 2}}
3	Pantry	0	0	0	0	2	{{2, 1}}
4	Master Bedroom	2	0	-1	1	-3	{{2, 2}, {3, 2}}
5	Master Bathroom	1	0	0	0	2	{{2, 2}}
6	Boiler Room	0	0	0	0	2	{{2, 1}}
7	Child Room 1	2	1	-1	0	-3	{{2, 3}}
8	Child Room 2	2	1	-1	0	-3	{{2, 3}}
9	Child Room 3	2	1	-2	0	-3	{{2, 3}}
10	Bathroom	0	0	0	0	2	{{2, 2}}
11	WC	0	0	0	0	2	{{1, 1}}
12	Guest Shower	0	0	0	0	2	{{2, 1}}
13	Guest Room	0	0	-1	0	2	{{2, 3}}
14	Study Room	2	1	-2	0	2	{{2, 3}}

structure of the modern city. An observation and judgment of photographs and the semantic differential method which belongs to the *psychological paradigm* has been described over 60 years ago [85].

This paper, however, focuses more on the user’s personal satisfaction from the SFH, therefore subjective evaluation of sights on the site is the most appropriate. A novel method has been implemented in order to systematically quantify the view quality (VQ) over the entire building plot for optimization calculations. At first, 64 photographs have been taken from eight points on site: four on its perimeter (A, B, G, H) and four inside (C, D, E, F). Fig. 5 shows the location of these points on site. From each point photographs have been taken in directions of eight octants. Fig. 6 shows eight such photographs taken from point D.

In principle, the photographs should be taken at various seasons as the landscape changes substantially throughout a year. Nevertheless, since all the views are evaluated in relation to each other, it was assumed that for the presentation of this framework, it is sufficient to evaluate one series of photographs taken at approximately the same time. Next, all the photographs have been evaluated by the authors in the following scale: 0 - poor, 1 - fair, 2 - good, 3 - excellent. For each octant, the VQ has been interpolated over the entire building plot in the

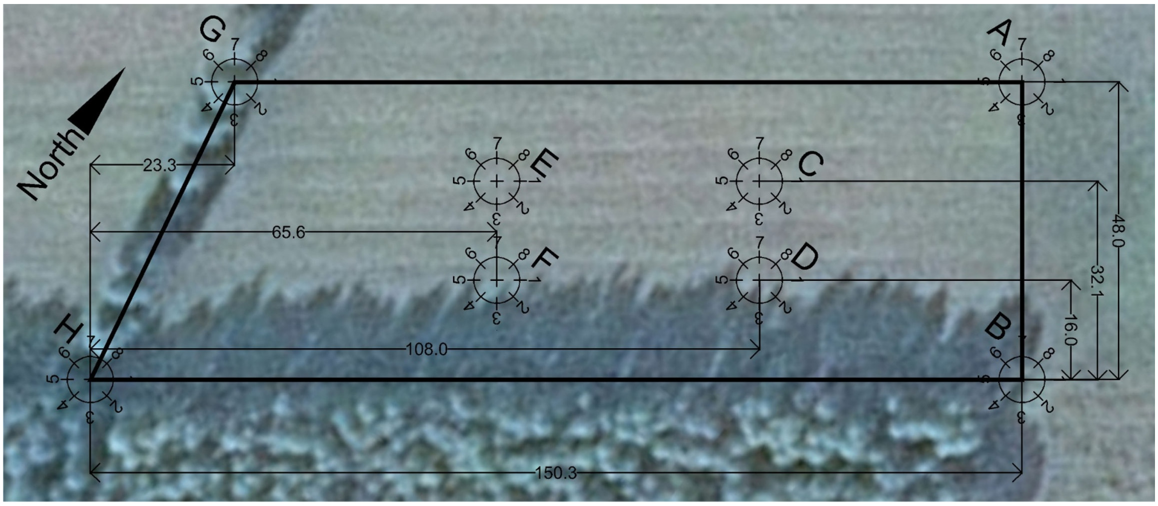

Fig. 5. Aerial view of the building plot with dimensions and the geographic orientation. Eight measurement points are indicated from A to H. The views are assessed at eight directions (1 to 8). The measurements are given in meters.

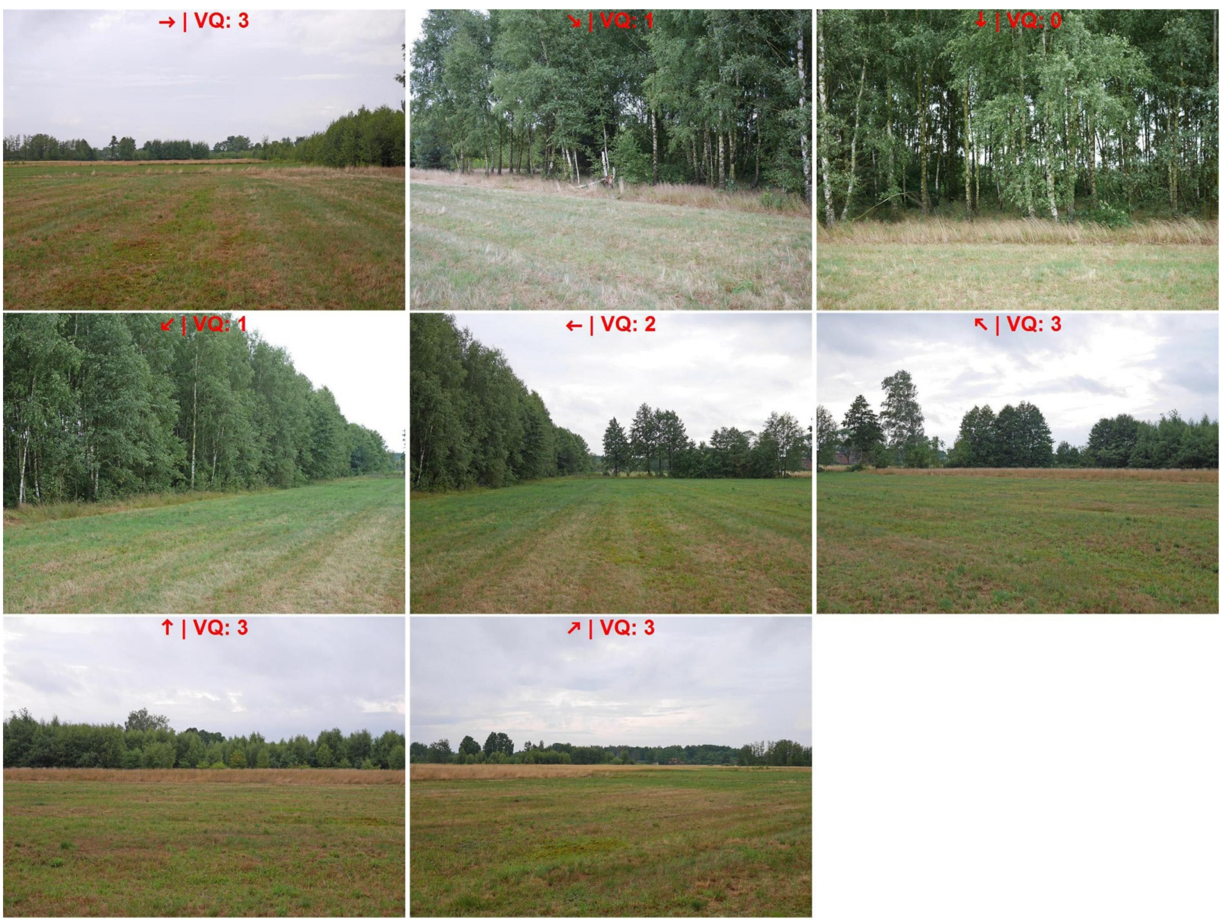

Fig. 6. The views from point D facing eight octants. The VQ value is shown for each view.

form of a heatmap (VQHM) as shown in Fig. 7.

3.2. The field measurement of the noise distribution on the building plot

The environmental noise in the building plot has been measured by the professional sound level meter SVAN 912A. This method provided interesting information about the noise conditions of the site. At first, at each point (A⋯H) A-weighted equivalent continuous sound level (L_{Aeq}) has been measured for a period of 20 minutes (Fig. 8). It was important to obtain all the readings in one day and with comparable nearby traffic loads. The building plot is located in a rural area, the L_{Aeq} measured values were in the range of 40 dBA. All these values are well in the acceptance range as stated by law permitting building constructions in the territory of the Republic of Poland [86]. This level of noise is lower than requirements even for hospitals in rural areas. The noise was not evenly distributed on the site, as shown in Fig. 8. Therefore, it should be taken into account during optimization in order to increase the inhabitants' comfort. It should also be noted that the measurements were

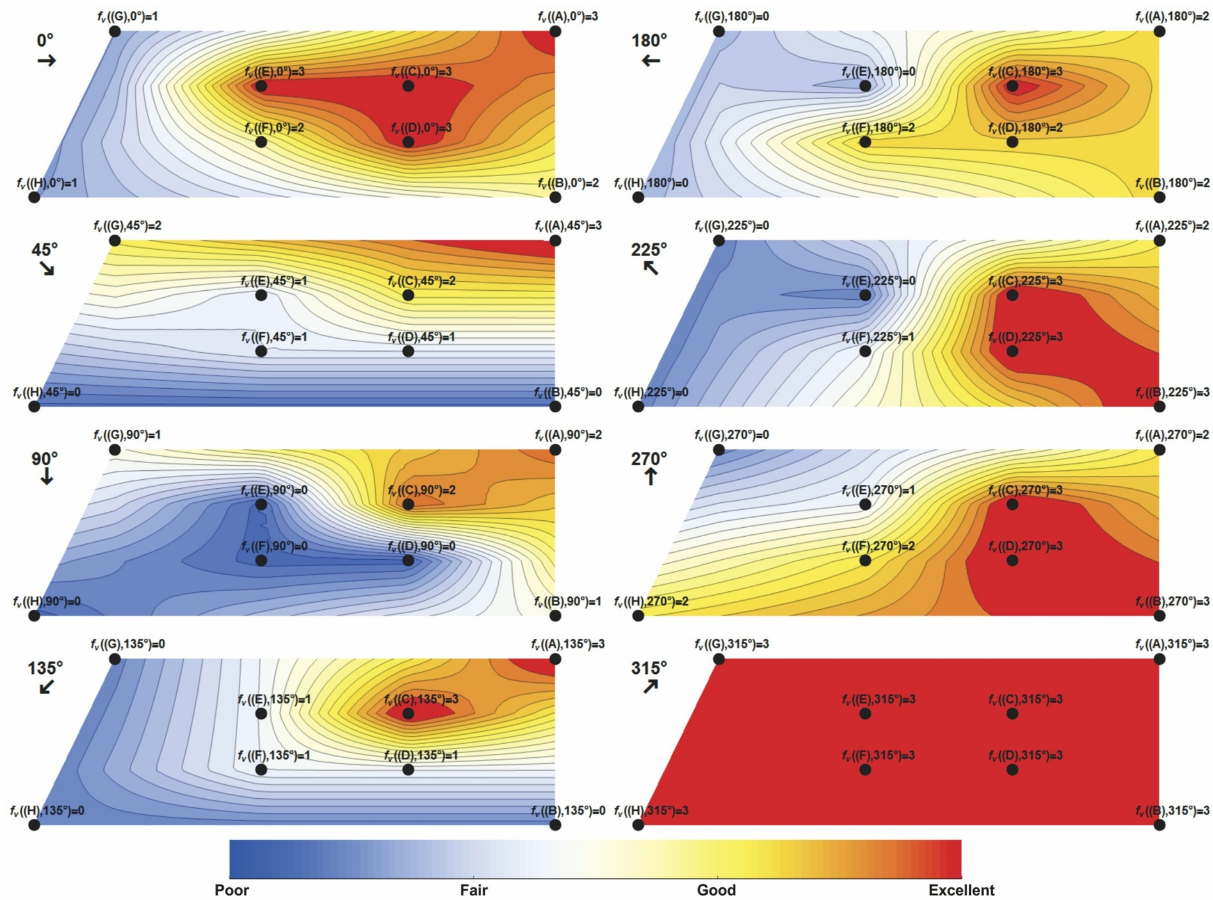

Fig. 7. View quality heatmap (VQHM) of the building plot in eight directions. Maximal value over the entire building plot for angle 315° means that in this direction the view is excellent from any position.

taken during fair weather and the noise may vary substantially in other conditions, depending e.g. on humidity. For example, passing vehicles during rain sound significantly louder.

3.3. Influence of the direct sunlight

Quality of living in a house is influenced by direct sunlight rays entering rooms through the windows. This is implemented in the presented framework in a simple, but effective way. Each room has assigned a weight-value which describes user preferences for sunlight at various times of day (here: Morning, Noon and Evening). For example, the user might prefer that: the morning Sun hitting the windows of a master bedroom is extremely preferrable ($W_{morninglight} = +3$), the sunlight at noon is neutral for this room ($W_{noonlight} = 0$), and the evening light should not penetrate this bedroom ($W_{eveninglight} = -1$).

In order to incorporate such preferences in the objective function, solely geographical directions of east, south and west are considered. This motivation comes from the fact that throughout the year, for the

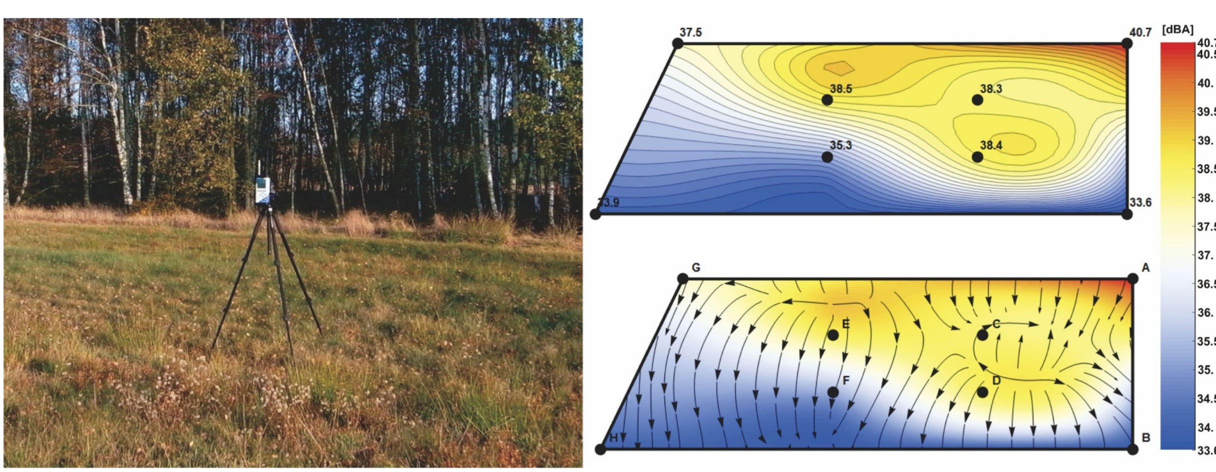

Fig. 8. On the left: the professional sound level meter SVAN 912A for measuring environmental noise placed on a tripod during operation at the point D. Top right: eight values (in dBA) of A-weighted equivalent sound level (L_{Aeq}) measured at points A$\cdots$H and interpolated over the entire building plot. Bottom right: the stream plot of the gradient of L_{Aeq}.

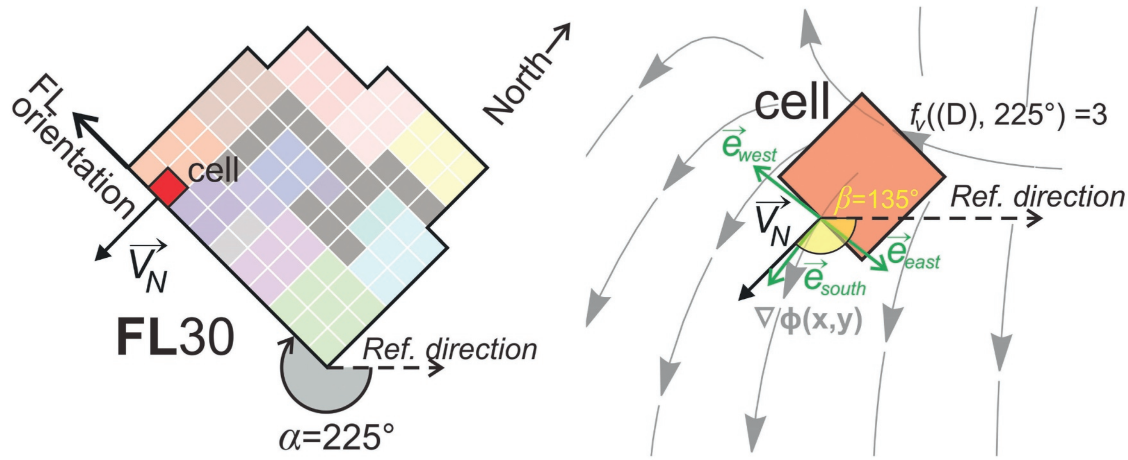

Fig. 9. On the left: FL30 placed in point D and oriented at 225° from the reference direction. On the right: the individual cell of this FL shown in further detail.

building plot located in the northern hemisphere, the Sun – on average – rises in the east, sets in the west and is at its highest position in the southern direction. For each grid cell having a window (i.e., facing outwards of the house), the cosine of the angle between a vector normal to the window area and a vector pointing into one of the geographical directions (east/south/west) is calculated. This value is multiplied by the associated weights and finally it contributes to the objective function.

4. Calculating the objective function

Defining the objective function for an optimization in the field of architecture is rather subjective. This is due to the fact that such an optimization process depends on the architect's and client's arbitrarily made decisions based on their personal preferences. The framework proposed here attempts to implement various types of quantifiable qualities into a meaningful single objective function.

The functional layout (FL) is laid out on a square grid of 1.5 × 1.5 m cells. There are four vectors normal to the cell's faces. If such a vector $\vec{v}_n$ is facing outward from the building, it contributes to the objective function *U*. *U* is a function of position (*x, y*) of FL on site and its rotation *α*. The total value of the objective function *U* is the sum of all contributions u_n made by cells facing outwards:

$$U(x, y, \alpha) = \sum_{\vec{v}_n \in N} u_n(x, y, \alpha, \vec{v}_n) \tag{1}$$

where *N* represents the set of all the cell's normal vectors facing outside of the FL.

U is maximized in the space (*x, y, α*). The contribution u_n of the vector $\vec{v}_n$ is calculated as a sum of quantified qualities related to the daylight, the noise exposure, and the importance of a window view. They can be summarized as follows:

- *View-quality* is a scalar function of three variables (*x, y, β*), where (*x, y*) is the viewer's position and *β* is the azimuth between the direction the viewer is facing and direction 1 (see Fig. 5). The exact values of $f_v(x, y, \beta)$ are linearly interpolated from the assessed values as shown in Fig. 7.
- *Noise-quality* is derived from the scalar noise measurements $\phi(x, y)$. At each point (*x, y*) the noise source direction is assumed to be parallel to the gradient $\nabla\phi$. The noise exposure is calculated by taking into account the angle between v_n and $\nabla\phi$ and its amplitude being proportional to $\phi(x, y)$. The field $\phi(x, y)$ is a linear interpolation of the measured values on site. Additionally, ϕ is scaled in such way that 0.5 is the minimal value corresponding to "fairly quiet" (33.6 dbA) and 1.0 (maximal) to be "noisy" (40.7 dbA), see Fig. 8. The degree of incorporating *direction* from which the noise is coming is handled by the additional parameter $0 \le \gamma \le 1$. It determines the amount of the noise-related penalty due to the facing direction (0–no dependence; 1–full dependence). In all the presented calculations $\gamma = 0.3$. The impact of noise on the objective function is then proportional to: $\phi(x, y)[1 - \gamma[1 + d'(\vec{v}_n, \nabla\phi(x, y))]]$.
- *Daylight-quality* is a function measuring average sunlight at morning, noon, and evening. The used angles are determined by geographical location, i.e., vectors pointing towards east, west and south ($\vec{e}_{\text{east}}$, $\vec{e}_{\text{west}}$, $\vec{e}_{\text{south}}$). The contribution to the objective function is proportional to the cosine of the angle between the normal vector $\vec{v}_n$ and $\vec{e}$ multiplied by the corresponding weights. For example, the influence of morning light is included in the U as: $W_{morninglight}\, d(\vec{v}_n, \vec{e}_{\text{east}})$.

In the above formulas, for calculating the contribution of the *noise-quality* and the *daylight-quality*, supplementary functions *d* and *d′* which take into account directions of noise and sun rays are needed. For any two vectors $\vec{a}$ and $\vec{b}$, let the function $d(\vec{a}, \vec{b})$ be defined as $d(\vec{a}, \vec{b}) = \vec{a}\cdot\vec{b}/|\vec{a}||\vec{b}|$ which is the cosine of the angle between $\vec{a}$ and $\vec{b}$ and $d'(\vec{a}, \vec{b}) = d(\vec{a}, \vec{b})$ if $d(\vec{a}, \vec{b}) \ge 0$;0 otherwise. The latter is used to ensure a correct sign for the penalty when calculating noise impact. Fig. 9 illustrates these parameters and their relationships.

As mentioned above, all the contributions are weighted by multiplying with the given parameters $w_{...}$. Summarizing, $u_n(x, y, \alpha, \vec{v}_n)$ for each normal vector is calculated as follows:

$$\begin{aligned} u_n(x, y, \alpha, \vec{v}_n) = w_{\text{view}} f_v(x, y, \beta) + w_{\text{morninglight}}\, d(\vec{v}_n, \vec{e}_{\text{east}}) \\ + w_{\text{noonlight}}\, d(\vec{v}_n, \vec{e}_{\text{south}}) \\ + w_{\text{eveninglight}}\, d(\vec{v}_n, \vec{e}_{\text{west}}) + w_{\text{noise}}\phi(x, y)[1 - \gamma[1 + d'(\vec{v}_n, \nabla\phi(x, y))]] \end{aligned} \tag{2}$$

The weights *w* depend on the cell's type ("Kitchen", "Bedroom", etc.) and their values are provided by the user; f_v is the interpolated *view-quality* function; $\vec{e}$ are vectors representing geographical directions.

The objective function is dimensionless and so are the weights and values assessing view quality. The daylight quality enters *U* as a non-dimensional number being the cosine of the angle between two vectors multiplied by a weight value. The noise measurements are normalized using two ad-hoc values, such as $\phi = 0.5$ for fairly quiet (33.6 dbA) and $\phi = 1.0$ for noisy (40.7 dbA). Obviously, the choice of noise normalization and values for weights determines the value of the objective function and thus the result of optimization. All these numbers were chosen according to the authors' experience and preferences.

In order to numerically find the global maximum of *U*(*x, y, α*), a

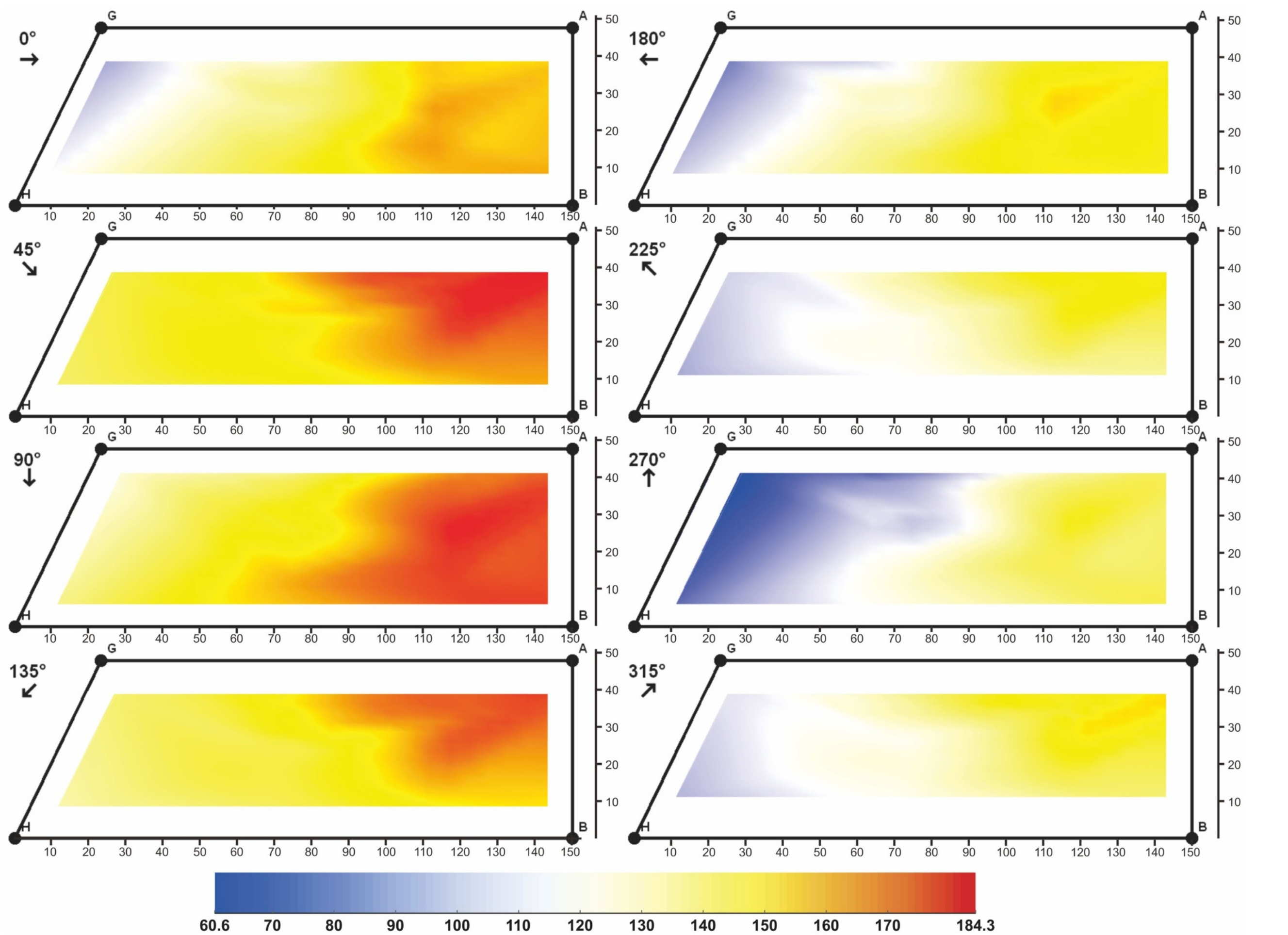

Fig. 10. Heatmaps of U for FL30 and 'balanced' preference-profile for eight octants. The maximal value of U was found at position x = 142.7m, y = 26.9m and azimuth $\alpha = 69^{\circ}$ (between angles 45° and 90°).

dedicated program in Python was written. The Broyden–Fletcher–Goldfarb–Shanno (L-BFGS-B, [87]) algorithm from optimization package SciPy was employed. It is a popular, iterative quasi-Newton method for minimum finding in which the Hessian matrix of second derivatives is not computed directly, but it is approximated by gradient evaluations from the previous steps. It has a good performance, also for "non-smooth" optimizations [88]. The numerical values of U at any point (x, y, α) in the search domain were calculated by means of linear interpolation between the measured points, i.e., the points A-H at which characteristics of the building plot were defined. For each FL, a number of initial "guesses" were "tried" (evenly spaced in the search space) in order to ensure that the global maximum was found.

An example of the objective function for the FL30 layout is shown in Fig. 10. $U(x, y)$ for eight various, constant values of α is presented as a collection of heatmaps over the building plot area. The optimal azimuth angle lies between directions 45 and 90°, and the house should be located somewhere in the top-right corner of the plot. Numerical calculations show that the exact global maximum is $(x = 138m, y = 36m, \alpha = 61^{\circ})$.

As mentioned above, it is common in the field of architecture to consider more than one seemingly ideal solution (i.e., the global optimum). The proposed framework easily allows for presentation of a set of potentially valuable candidate solutions. For example, it is possible to select geographically distinct FLs (which are separated by a given distance) and still have a comparable value of U. Therefore, the final result of the optimization is a ranked list of a number of FLs $\{FL, x, y, \alpha\} \to U$.

The maximum value of the objective function U corresponds to a single spot on the given building plot for a certain FL and preference profile. Formally, the best solution for a given profile, is a layout which gives the largest value of U in the (x, y, α) space where all 30 layouts are considered. In addition to this, one can consider *a universality* of a FL for a given building plot. It is understood as the averaged suitability of placing the FL *somewhere* on the plot. This is quantified as the mean value of U integrated over the entire search domain (x, y, α) for a given FL and preferences, and is denoted as $\overline{U}$.

This means that, for example, there might exist an FL_A which is the optimal one, in the sense that placing FL_A at a given point gives the maximum value of U. At the same time, there might exist another layout, FL_B, which has a smaller $\max U_{FL_B} < \max U_{FL_A}$, however its mean value of the objective function can be larger $\overline{U_{FL_B}} > \overline{U_{FL_A}}$. For the considered case study, this actually happened for the 'noise' profile, see Fig. 16. The optimum solution is the FL17, having universality $\overline{U_{FL17}} = 0.34$. At the same time, there exist layouts being – on average – more suitable for the building plot, having $\overline{U_{FL6}} = 0.38$ or $\overline{U_{FL13}} = 0.38$, and the maximum value of U equal to 0.87 and 0.85 respectively.

5. Results and discussion

The optimization algorithm described above answers the following questions:

1. What is the best FL for 'view' preference-profile in this particular building plot, where should it be placed and at which direction to

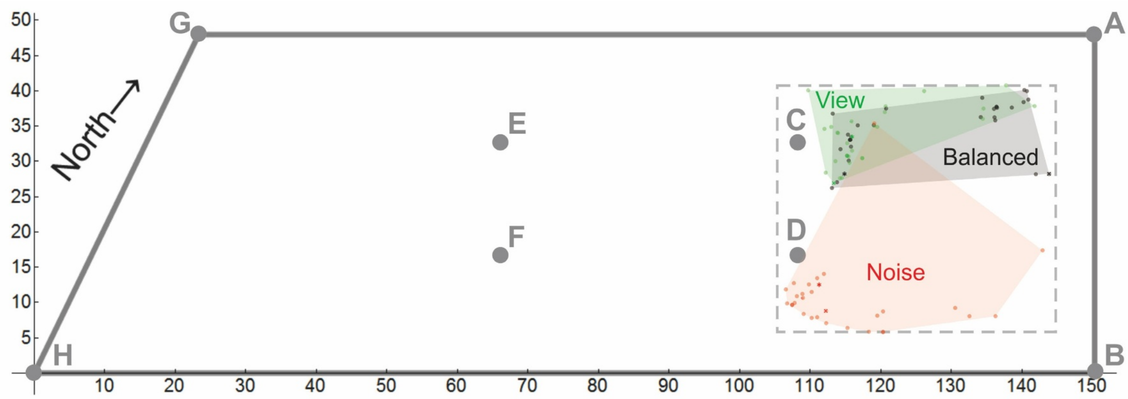

Fig. 11. The best locations for: 'view', 'noise', and 'balanced' preference-profiles are shown on the building plot in: green, red and black, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

maximize the overall satisfaction of a user according to a mathematically expressed preference.

2. As above for the 'noise' and 'balanced' preference-profiles
3. Additionally: what is the most universal FL, in other words which FL would perform relatively well regardless of its position on this building plot?

5.1. *The best FLs for: 'view', 'noise' and 'balanced' preference-profiles*

Fig. 11 shows the best locations on the building plot for all 30 FLs. For clarity, the envelopes for each group of results are shown. Table 5 in the Appendix collects the complete results in a tabular form.

As Fig. 11 indicates, almost all of the best *balanced* and *view* -preferred apartments are localized in the upper, right part of the building plot. This is because the view quality in this area is acceptable and noise is not important for these preference-profiles, in particular for *view*. On the other hand, *noise* is shifted closer to the trees boundary where the noise is substantially reduced. This is achieved at expense of the view quality.

Fig. 12 shows the results in more detail. The value of U in the plotted points is maximal for a given FL.

As Fig. 12 shows in more detail, the *balanced* solutions tend towards the right part of the plot where the view quality has slightly lesser quality, however, by proper rotation, the directional noise exposure is reduced.

Fig. 13 shows the best FLs for 'view', 'noise' and 'balanced' preference-profiles rotated for the best orientation.

One of the impacts of the optimization which can be noticed is the location of the Living Room (labeled as '1'; shown in green). This room tends to be placed in the vicinity of the point C in the way that its normal vectors face direction in the range of angles 130°-315°. This makes it possible to put other rooms in positions with a good view, shield bedrooms from noise, and maximize sunlight according to the stated preferences. Indeed, as Fig. 7 indicates, the overall views from point C in all directions are the best (total score of 22).

Fig. 14 shows the bar chart collecting the maximal and mean values of U for each FL in the "balanced" preference-profile. For clarity, the values have been normalized, so 1 and 0 correspond to: the overall best and worst solutions achieved, respectively. As Fig. 14 indicates, for these conditions there are five outstanding FLs: 30, 14, 27, 17, and 24.

Fig. 15 shows the analogous bar chart for the *view* preference-profile.

As Fig. 15 indicates, for these conditions there are three or four outstanding FLs: 22, 14, 17, and possibly 30. Fig. 16 shows the bar chart of the best and mean results for the *noise* preference-profile.

As Fig. 16 indicates, for these conditions there is practically a single outstanding FL, namely 17.

5.2. *What is the universal functional layout for this building plot?*

In the section above, a number of the best FLs for specific preference-profiles, whose performance strongly depends on the location on the building plot have been found. However, a natural question arises: *if the actual possible location of the SFH on the given building plot (due to e.g. geological restrictions) is not absolutely certain, what would be a "safe" functional layout?* In other words, which FL would perform "decently" in any position. By looking at the mean values in Fig. 14, it can be assumed that for a *balanced* preference-profile FL30 is not only the global maximum, but due to the highest mean value, it is also the most universal solution. Fig. 17 shows FL30 in a little more detail along with a density plot maximizing the quality of this solution by proper orientation on the building plot.

- For *balanced* preference-profile FL30 is both the global optimum and the "safest bet". In the case of *view*, it is also very competitive: the best three are: FL22, 14, and 17, while the "safest" are: FL17, 22, and 14.
- For *noise* preference-profile the best three FLs are: 17, 27, and 22, while the "safest" are very different, namely: FL13, 6, and 8.
- Nevertheless, since the *balanced* preference-profile seems the most universal, FL30 can be considered as the overall most suitable solution for this building plot.

6. Future work

Presented objective function can be easily adapted to specific and complex conditions. Another practical criteria would be: minimization of earthworks on site and minimization (or even prohibition) of existing tree removal. Both objectives have been successfully implemented by the authors in an analogous problem of optimization of a modular truss layout in [89]. Other possible objectives could be: the costs associated with construction; connection to water, gas, electricity and the internet; shading from the elements of environments.

The described optimization procedure is naturally performed – to a certain degree – by an architect when visiting the building plot or scrutinizing its map. By utilizing modern computational power one can quickly scan a potentially enormous database of building plans (substantially more than the 30 FLs discussed here) and associated construction costs. To what degree such computations would outperform human choices remains to be discovered. An interesting area for research is to survey and evaluate existing buildings and then compare the results with those produced by the presented framework.

The most promising direction of future research is a large-scale optimization of entire settlements. The optimization will be significantly more complicated since the objective function for each

Table 5
The complete results for all three preference-profiles. The best results are highlighted. $\tilde{U}_B$, $\tilde{U}_V$, and $\tilde{U}_N$ stand for normalized quality of: "balanced", "view", and "noise" preference profiles, respectively.

FL	Balanced				View				Noise			
	X	Y	α	$\tilde{U}_B$	X	Y	α	$\tilde{U}_V$	X	Y	α	$\tilde{U}_N$
1	136	36	146	0.17	119	29	137	0.47	109	10	41	0.56
2	136	36	146	0.17	119	29	137	0.47	109	10	41	0.56
3	136	36	146	0.19	134	34	146	0.55	113	8	66	0.56
4	136	35	146	0.11	134	35	146	0.42	110	10	32	0.29
5	134	37	321	0.23	114	33	315	0.33	111	11	44	0.69
6	134	34	324	0.46	115	33	315	0.58	109	12	56	0.77
7	136	34	325	0.6	114	27	93	0.71	112	8	8	0.66
8	117	31	225	0.56	117	29	225	0.66	121	6	270	0.62
9	117	31	225	0.56	117	29	225	0.66	121	6	270	0.62
10	117	31	225	0.56	117	29	225	0.71	114	14	292	0.59
11	120	33	225	0.41	120	33	225	0.56	131	10	316	0.35
12	117	30	225	0.4	120	33	225	0.44	111	9	280	0.72
13	117	32	223	0.76	117	31	224	0.7	142	17	257	0.73
14	116	27	274	0.97	117	32	225	0.97	136	8	318	0.72
15	117	29	225	0.24	117	30	225	0.	110	11	202	0.29
16	116	30	225	0.02	112	38	135	0.03	120	9	207	0.03
17	140	38	141	0.91	117	34	135	0.89	114	9	177	1.
18	140	38	145	0.65	115	32	224	0.49	113	13	199	0.58
19	117	32	225	0.65	121	35	225	0.6	117	7	189	0.77
20	140	37	149	0.11	116	26	50	0.	132	8	155	0.11
21	138	36	150	0.	141	36	144	0.02	121	9	160	0.
22	115	25	103	0.7	115	26	92	1.	111	11	173	0.79
23	115	26	98	0.62	116	26	94	0.62	112	13	120	0.54
24	139	36	62	0.85	115	32	45	0.76	114	8	105	0.7
25	118	33	135	0.27	127	38	135	0.31	120	33	135	0.56
26	115	35	225	0.23	115	29	281	0.26	110	13	217	0.57
27	122	35	224	0.92	122	36	224	0.79	113	13	210	0.84
28	136	34	146	0.02	117	29	47	0.24	109	10	180	0.57
29	141	27	71	0.58	117	28	66	0.47	112	12	118	0.64
30	143	27	69	1.	137	38	50	0.85	119	6	108	0.66

apartment will depend also on the room configurations of other apartments. The buildings will interfere with each other in therms of the "view-quality" or noise characteristics. Consequently, the global objective function to be optimized will have to reflect such complex interactions among all the buildings. A genetic algorithm-based hybrid technique for layout planning of residential houses where visibility between neighboring settlements was minimized and and to maximize the direction of facades to a favorite view was maximized has been presented in [90].

Moreover, the exact number of apartments to be placed on a given building plot may not be known beforehand, and this very problem can be a subject to optimization. This task may be of special importance for building developers wanting to maximize profits, as well as customer satisfaction at the same time. It should be stressed here, that for such a complex optimization problem, any simple gradient-based search will not suffice. More sophisticated methods need to be deployed, for example metaheuristics [91]. The authors have successfully implemented modern heuristics to closely related multicriterial optimization of modular truss layouts in constrained environments considering: minimization of its "geometrical complexity" and the number of modules [92], minimization of network distance of a multi-branch layout [93].

The introduction of "green building" standards promotes performance-driven architectural design worldwide [94,95]. For a review of requirements of the indoors air quality in 55 "green building" schemes with 31 international certifications see [96]. Moreover, the research on integrating the issues of energy performance into the early stage of design in architecture has also been extensive. As a result architects increasingly become aware of these issues and knowledgeable of relevant computational tools. Moreover several relatively advanced programs such as *McNeel Rhinoceros*, and its parametric modeling environment *Grasshopper*, and other open-source platforms are available for free. For example Ref. [97] uses *Rhinoceros* for geometry modeling in optimization of a free-form surface according to the thermal load characteristics.

This paper focuses on a different kind of building-performance which is subjective and relates to the immediate comfort of a user. It pertains to *Venustatis* - the last but not least of the *three principles of Architecture* formulated over two millenia ago by Roman architect Vitruvius [98]:

1. Durability (L. firmitatis) - it should stand up robustly and remain in good condition
2. Utility (L. utilitatis) - it should be useful and function well for the people using it
3. Beauty (L. venustatis)- it should delight people and raise their spirits.

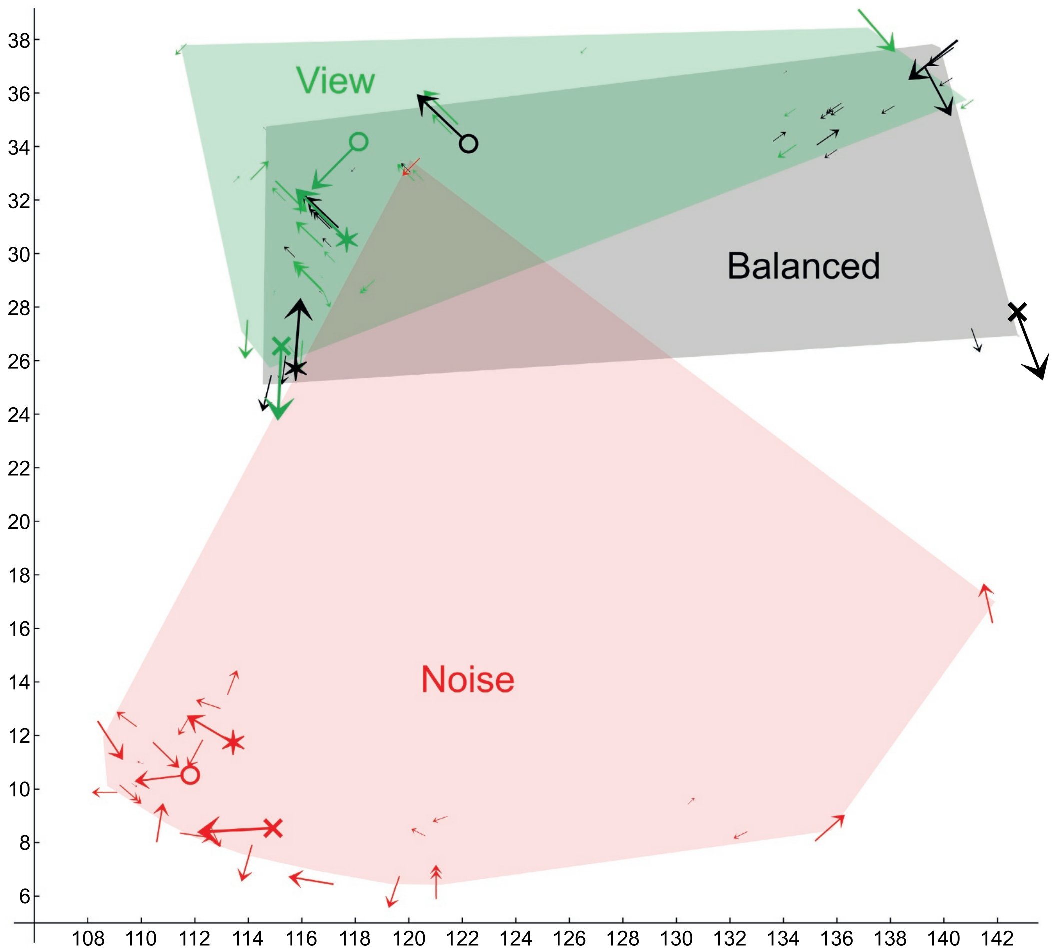

Fig. 12. Enlarged part of the building plot where the results are located. The best results for: 'view', 'noise', and 'balanced' preference-profiles are shown in: green, red and black, respectively. The directions of the arrows indicate the best orientations. The sizes of the arrows are proportional to the quality of solutions. The best, second best and third best solutions are indicted by the symbols at the end of an arrow: ×, *, and ∘, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

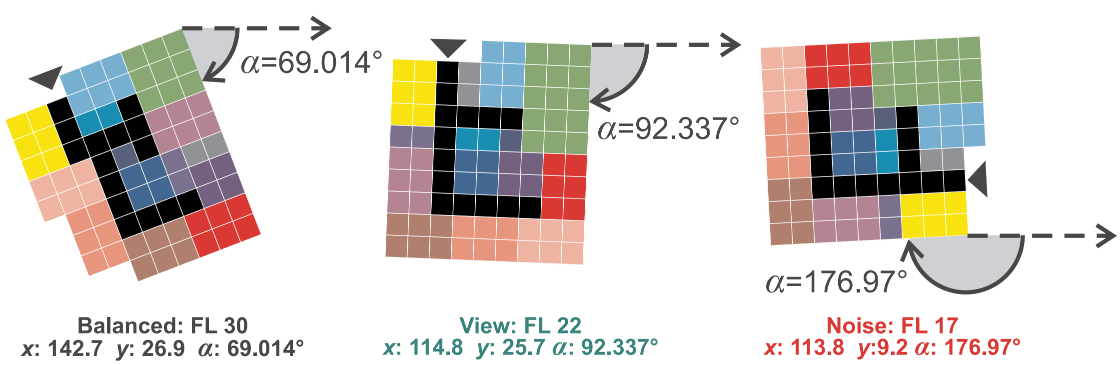

Fig. 13. The best FLs for: 'balanced', 'view', and 'noise' preference-profiles rotated for the best orientation are: FL30, FL22, and FL17, respectively. Black triangle indicates the entrance.

For creative applications of computational intelligence methods to these three principles see:

- Durability: a graph-theoretic optimization technique for finding the ideal solutions for retrofitting of an existing footbridge with self-supporting modular access ramp [99], a folding-module system for creating pipe-like dynamically reconfigurable systems for extreme habitats [100], application of evolutionary algorithms for effective finding of near-optimal solutions for optimization of a single [92] and multi-branch [93] modular skeletal system, massive parallalization with GPU applied for multi-objective optimization of modular structures in real environments [89].
- Utility: graph-theoretic method combined with artificial neural network in architectural layout optimization [33], an architectural design aid for initial crowd-dynamics analysis with a user-friendly agent-based model [76], a computational tool for automated

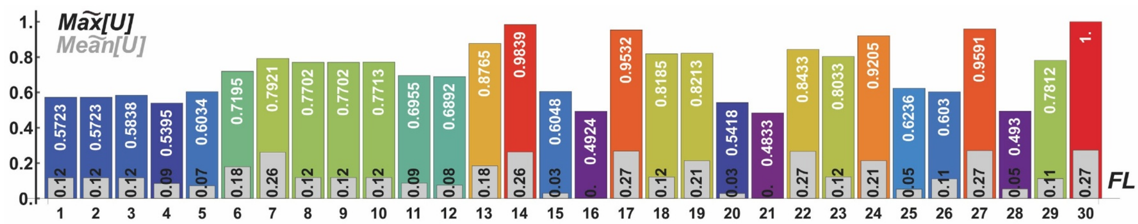

Fig. 14. Balanced: the maximal and mean values of the objective function max U, for all 30 considered FLs. The maximal values are shown in color reflecting their quality. Mean values are shown in gray.

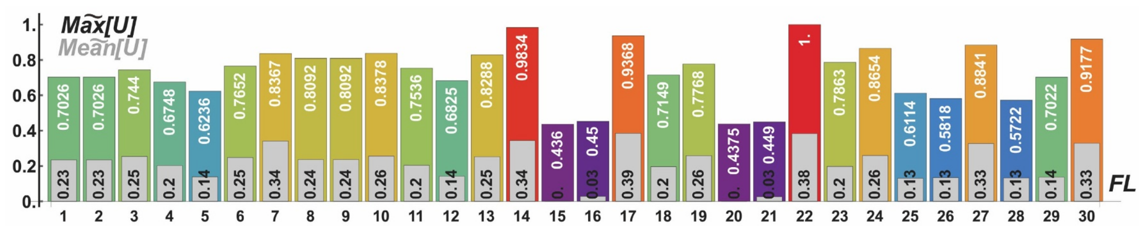

Fig. 15. View: the maximal and mean values of the objective function max U. Color convention as in Fig. 14.

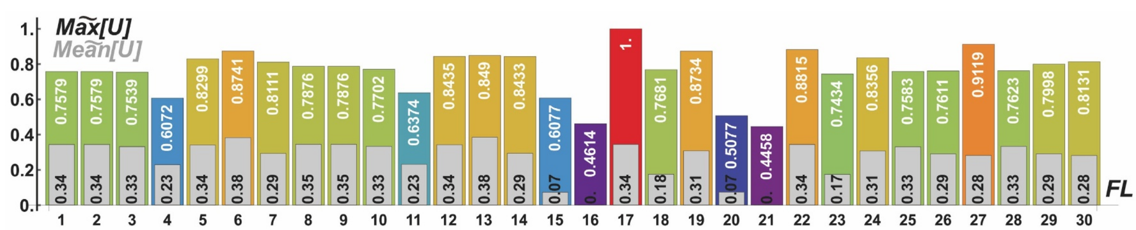

Fig. 16. Noise: the maximal and mean values of the objective function max U. Color convention as in Fig. 14.

evaluation of urban squares [82].

- Beauty: application of cellular automata for shading of building facades [101], the emergence [102] and shading control [103] in such system, the aesthetic properties of such system based on three regular tessellations [73].

The energy performance can be also implemented by using the presented framework. This could be done iteratively by the external specialized software mentioned above, and the result after weighting would be appended to the objective function U. Such an addition, however, will be computationally expensive. Therefore combination of metaheuristic methods and parallelization would be rational.

7. Conclusions

- A new framework for simultaneous optimization of a floor plan of a one-story single family house with its location and orientation on a given building plot has been presented.
- One of the novel contributions of this paper is the use of subjective aesthetic impression as one of the optimization criteria, namely the quality of the outside view. Another criterion was insolation, which is a classic performance-driven objective commonly used in architectural optimization [94,95]. The third objective, which is not as common as the latter is acoustic comfort.
- Presented framework can be naturally expanded for additional criteria.
- The presented framework is tested with a realistic case-study of a 14-room single family house located on an existing building plot. The results are feasible from the perspective of architectural design.

Declaration of Competing Interest

All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.

This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.

The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

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Appendix

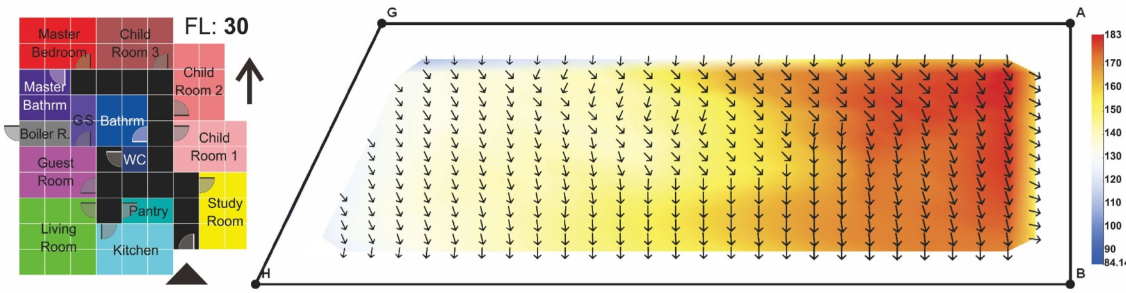

Fig. 17. On the left: FL30 with the entrance and doors shown by: a triangle and quadrants, respectively. GS stands for Guest Shower. On the right: interpolated density plot of the array of maximal *U* values for FL30 at best orientations, which are indicated by black arrows.

Supplementary material

Supplementary material associated with this article can be found, in the online version, at 10.1016/j.advengsoft.2019.102766.

References

[1] Michalewicz Z, Dasgupta D, Le Riche RG, Schoenauer M. Evolutionary algorithms for constrained engineering problems. Comput Ind Eng 1996;30(4):851–70.
[2] Sowa J. Conceptual Graphs. In: van Harmelen F, Lifschitz V, Porter B, editors. Handbook of Knowledge Representation. Amsterdam, Netherlands: Elsevier; 2008. p. 213–37.
[3] Leśniakowska M. Co to jest architektura? Warsaw: Kanon; 1996.
[4] Cross N. Natural intelligence in design. Des Stud 1999;20(1):25–39.
[5] Rolls ET. On the brain and emotion. Behav Brain Sci 2000;23(2):219–28.
[6] Church A. A set of postulates for the foundation of logic. Ann Math 1932:346–66.
[7] Turing A. On Computable Numbers, with an Application to the Entscheidungsproblem. Proc Lond Math Soc 1936;42(2):230–65.
[8] Turing A. Computability and λ-definability. J Symbolic Logic 1937;2(4):153–63.
[9] Sönmez NO. A review of the use of examples for automating architectural design tasks. Comput-Aided Des 2018;96:13–30.
[10] Beghini LL, Beghini A, Katz N, Baker WF, Paulino GH. Connecting architecture and engineering through structural topology optimization. Eng Struct 2014;59:716–26.
[11] Zawidzki M, Nishinari K. Modular Truss-Z system for self-supporting skeletal free-form pedestrian networks. Adv Eng Softw 2012;47(1):147–59. https://doi.org/10.1016/j.advengsoft.2011.12.012.
[12] Zawidzki M., Jankowski Ł.. Optimization of modular Truss-Z by minimum-mass design under equivalent stress constraint. Smart Struct Syst 21(3). doi:10.12989/sss.2018.21.6.715.
[13] Zawidzki M, Jankowski Ł. Multiobjective optimization of modular structures: Weight versus geometric versatility in a Truss-Z system. Comput Aided Civ Inf 2019;34:1026–40.
[14] Tam KY. Genetic algorithms, function optimization, and facility layout design. Eur J Oper Res 1992;63(2):322–46.
[15] Sharpe R, Marksjö BS. Solution of the facilities layout problem by simulated annealing. Comput Environ Urban Syst 1986;11(4):147–54.
[16] Yeh I-C. Architectural layout optimization using annealed neural network. Autom Constr 2006;15(4):531–9.
[17] Liang LY, Chao WC. The strategies of tabu search technique for facility layout optimization. Autom Constr 2008;17(6):657–69.
[18] García-Hernández L, Pierreval H, Salas-Morera L, Arauzo-Azofra A. Handling qualitative aspects in unequal area facility layout problem: an interactive genetic algorithm. Appl Soft Comput 2013;13(4):1718–27.
[19] Liu J, Liu J. Applying multi-objective ant colony optimization algorithm for solving the unequal area facility layout problems. Appl Soft Comput 2019;74:167–89.
[20] Allahyari MZ, Azab A. Mathematical modeling and multi-start search simulated annealing for unequal-area facility layout problem. Expert Syst Appl 2018;91:46–62.
[21] Matai R. Solving multi objective facility layout problem by modified simulated annealing. Appl Math Comput 2015;261:302–11.
[22] Gonçalves JF, Resende MG. A biased random-key genetic algorithm for the unequal area facility layout problem. Eur J Oper Res 2015;246(1):86–107.
[23] Buffa ES. Allocating facilities with CRAFT. Harvard Bus Rev 1964;42(2):136–59.
[24] Jo JH, Gero JS. Space layout planning using an evolutionary approach. Artif Intell Eng 1998;12(3):149–62.
[25] Liggett RS. Automated facilities layout: past, present and future. Autom Constr 2000;9(2):197–215.
[26] Rodrigues E, Gaspar AR, Gomes Á. An evolutionary strategy enhanced with a local search technique for the space allocation problem in architecture, part 1: methodology. Comput-Aided Des 2013;45(5):887–97.
[27] Rodrigues E, Gaspar AR, Gomes Á. An evolutionary strategy enhanced with a local search technique for the space allocation problem in architecture, part 2: validation and performance tests. Comput-Aided Des 2013;45(5):898–910.
[28] Flemming U, Baykan CA, Coyne RF, Fox MS. Hierarchical generate-and-test vs constraint-directed search. Artificial Intelligence in Design '92. Springer; 1992. p. 817–38.
[29] Flemming U, Coyne R, Woodbury R. Seed: A software environment to support the early phases in building design. Proceedings of IKM94. 1994. p. 5–10.
[30] Akin Ö, Dave B, Pithavadian S. Heuristic generation of layouts (HeGel): based on a paradigm for problem structuring. Environ Plan B 1992;19(1):33–59.
[31] Baykan CA. Formulating Spatial Layout as a Disjunctive Constraint Satisfaction Problem. PhD Thesis, Carnegie Mellon University. 1991.
[32] Terzidis K. Algorithmic architecture. 1st ed. London: Routledge; 2006.
[33] Zawidzki M, Tateyama K, Nishikawa I. The constraints satisfaction problem approach in the design of an architectural functional layout. Eng Optim 2011;43(9):943–66.
[34] Guo Z, Li B. Evolutionary approach for spatial architecture layout design enhanced by an agent-based topology finding system. Front Archit Res 2017;6(1):53–62.
[35] Szokolay S. Introduction to architectural science. 1st ed. London: Routledge; 2012.
[36] Voelker C, Beckmann J, Koehlmann S, Kornadt O. Occupant requirements in residential buildings: an empirical study and a theoretical model. Adv Build Energy Res 2013;7(1):35–50.
[37] Zhai Y, Wang Y, Huang Y, Meng X. A multi-objective optimization methodology for window design considering energy consumption, thermal environment and visual performance. Renew Energy 2019;134:1190–9.
[38] Montana SLF, Sanseverino ER. A review on optimization and cost-optimal methodologies in low-energy buildings design and environmental considerations. Sustain Cities Soc 2018.
[39] Evins R. A review of computational optimisation methods applied to sustainable building design. Renew Sustain Energy Rev 2013;22:230–45.
[40] Hamedani Z, Solgi E, Skates H, Hine T, Fernando R, Lyons J, et al. Visual discomfort and glare assessment in office environments: a review of light-induced physiological and perceptual responses. Build Environ 2019;153:267–80.
[41] Choudhary R, Malkawi A, Papalambros P. Analytic target cascading in simulation-based building design. Autom Constr 2005;14(4):551–68.
[42] Both B, Szánthó Z, Goda R. Draught comfort in a slot-ventilated room at various inlet aspect ratios. Energy Procedia 2017;112:352–9.
[43] Caldas LG, Norford LK. A design optimization tool based on a genetic algorithm. Autom Constr 2002;11(2):173–84.
[44] Cutler B, Sheng Y, Martin S, Glaser D, Andersen M. Interactive selection of optimal fenestration materials for schematic architectural daylighting design. Autom Constr 2008;17(7):809–23.
[45] Mahdavi A, Suter G. On the implications of design process views for the development of computational design support tools. Autom Constr 1998;7(2–3):189–204.
[46] Yi YK, Kim H. Agent-based geometry optimization with genetic algorithm (GA) for tall apartments solar right. Solar Energy 2015;113:236–50.
[47] Yi YK. Building facade multi-objective optimization for daylight and aesthetical perception. Build Environ 2019;156:178–90.
[48] Berglund B, Lindvall T, Schwela DH. Guidelines for community noise. Geneve: World Health Organization; 1999.
[49] Muzet A. Environmental noise, sleep and health. Sleep Med Rev

2007;11(2):135–42.
[50] Schultz TJ. Synthesis of social surveys on noise annoyance. J Acoust Soc Am 1978;64(2):377–405.
[51] Kryter KD. Community annoyance from aircraft and ground vehicle noise. J Acoust Soc Am 1982;72(4):1222–42.
[52] Finegold LS, Harris CS, von Gierke HE. Community annoyance and sleep disturbance: updated criteria for assessing the impacts of general transportation noise on people. Noise Control Eng J 1994;42(1).
[53] Miedema HM, Vos H. Exposure-response relationships for transportation noise. J Acoust Soc Am 1998;104(6):3432–45.
[54] Miedema H, Oudshoorn C. Annoyance from transportation noise: relationships with exposure metrics DNL and DENL and their confidence intervals. Environ Health Perspect 2001;109(4):409–16.
[55] Miedema HM, Vos H. Associations between self-reported sleep disturbance and environmental noise based on reanalyses of pooled data from 24 studies. Behav Sleep Med 2007;5(1):1–20.
[56] Lee PJ, Park SH, Jeong JH, Choung T, Kim KY. Association between transportation noise and blood pressure in adults living in multi-storey residential buildings. Environ Int 2019;132:105101.
[57] Ryu J, Song H. Effect of building façade on indoor transportation noise annoyance in terms of frequency spectrum and expectation for sound insulation. Appl Acoust 2019;152:21–30.
[58] Chung WK, Chau CK, Masullo M, Pascale A. Modelling perceived oppressiveness and noise annoyance responses to window views of densely packed residential high-rise environments. Build Environ 2019;157:127–38.
[59] Machairas V, Tsangrassoulis A, Axarli K. Algorithms for optimization of building design: a review. Renew Sustain Energy Rev 2014;31:101–12.
[60] Waibel C, Wortmann T, Evins R, Carmeliet J. Building energy optimization: an extensive benchmark of global search algorithms. Energy Build 2019;187:218–40.
[61] Si B, Wang J, Yao X, Shi X, Jin X, Zhou X. Multi-objective optimization design of a complex building based on an artificial neural network and performance evaluation of algorithms. Adv Eng Inform 2019;40:93–109.
[62] Chardon S, Brangeon B, Bozonnet E, Inard C. Construction cost and energy performance of single family houses: from integrated design to automated optimization. Autom Constr 2016;70:1–13.
[63] Michalek J, Choudhary R, Papalambros P. Architectural layout design optimization. Eng Optim 2002;34(5):461–84.
[64] Palladio A. I quattro libri dell'Architettura. Hildesheim: Georg Olms Verlag; 1999.
[65] Mitrović B. Palladio's theory of proportions and the second book of the "Quattro libri dell'Architettura" J Soc Archit Historians 1990;49(3):279–92.
[66] Meissner M. A novel method for determining optimum dimension ratios for small rectangular rooms. Arch Acoust 2018;43(2):217–25.
[67] Gipps PG. Simulation of pedestrian traffic in buildings. Technical Report. Karlsruhe: Institut fur Verkehrswesen Universitat Karlsruhe; 1987.
[68] Blue V, Adler J. Cellular automata microsimulation of bidirectional pedestrian flows. Transp Res Rec: J Transp Res Board 1999(1678):135–41.
[69] Rajewsky N, Santen L, Schadschneider A, Schreckenberg M. The asymmetric exclusion process: comparison of update procedures. J Stat Phys 1998;92(1–2):151–94.
[70] Kretz T, Schreckenberg M. The F.A.S.T.-Model. Cellular Automata. Berlin: Springer; 2006. p. 712–5.
[71] Chavey D. Tilings by regular polygonsii: a catalog of tilings. Comput Math Appl 1989;17(1–3):147–65.
[72] Kepler J. Harmonice mundi. English Edition: Harmonies of the World 1938;5.
[73] Zawidzki M. Dynamic shading of a building envelope based on rotating polarized film system controlled by one-dimensional cellular automata in regular tessellations (triangular, square and hexagonal). Adv Eng Inform 2015;29(1):87–100.
[74] Weidmann U. Transporttechnik der Fussgänger: Transporttechnische Eigenschaften des Fussgängerverkehrs (Literaturauswertung). Zürich: ETH; 1993.
[75] Schadschneider A, Klingsch W, Klüpfel H, Kretz T, Rogsch C, Seyfried A. Evacuation dynamics: empirical results, modeling and applications. Encyclopedia of complexity and systems science. Springer; 2009. p. 3142–76.
[76] Zawidzki M, Chraibi M, Nishinari K. Crowd-Z: the user-friendly framework for crowd simulation on an architectural floor plan. Pattern Recognit Lett 2014;44:88–97.
[77] Ulrich RS. View through a window may influence recovery from surgery. Science 1984;224(4647):420–1.
[78] Ulrich RS. Visual landscapes and psychological well-being. Landscape Res 1979;4(1):17–23.
[79] Ulrich RS. Aesthetic and affective response to natural environment. Behavior and the natural environment. 6. Boston: Springer; 1983. p. 85–125.
[80] Nasar JL, Terzano K. The desirability of views of city skylines after dark. J Environ Psychol 2010;30(2):215–25.
[81] Lothian A. Landscape and the philosophy of aesthetics: is landscape quality inherent in the landscape or in the eye of the beholder? Landscape Urban Plan 1999;44(4):177–98.
[82] Zawidzki M. Automated geometrical evaluation of a plaza (town square). Adv Eng Softw 2016;96:58–69.
[83] Taylor N. Legibility and aesthetics in urban design. J Urban Des 2009;14(2):189–202.
[84] Perovic S, Folic NK. Visual perception of public open spaces in Niksic. Procedia-Social Behav Sci 2012;68:921–33.
[85] Suci GJ, Tannenbaum PH. The measurement of meaning. Urbana: University of Illinois Press; 1957.
[86] Rozporzadzenie Ministra Srodowiska z dnia 14 czerwca 2007r. w sprawie dopuszczalnych poziomow halasu w srodowisku, Dz.U. 2014 poz. 112.
[87] Fletcher R. Practical Methods of Optimization, 2nd Edition. Wiley978-1-118-72318-0; 2013.
[88] Curtis FE, Que X. A quasi-newton algorithm for nonconvex, nonsmooth optimization with global convergence guarantees. Math Program Comput 2015;7(4):399–428.
[89] Zawidzki M, Szklarski J. Effective multi-objective discrete optimization of Truss-Z layouts using a GPU. Appl Soft Comput 2018;70:501–12. https://doi.org/10.1016/j.asoc.2018.05.042.
[90] El Ansary AM, Shalaby M. Evolutionary optimization technique for site layout planning. Sustain Cities Soc 2014;11:48–55.
[91] Talbi E-G. Metaheuristics: from design to implementation. 74. John Wiley & Sons; 2009.
[92] Zawidzki M, Nishinari K. Application of evolutionary algorithms for optimum layout of truss-z linkage in an environment with obstacles. Adv Eng Softw 2013;65:43–59.
[93] Zawidzki M. Optimization of multi-branch Truss-Z based on evolution strategy. Adv Eng Softw 2016;100:113–25.
[94] Shi X, Yang W. Performance-driven architectural design and optimization technique from a perspective of architects. Autom Constr 2013;32:125–35.
[95] Nembrini J, Samberger S, Labelle G. Parametric scripting for early design performance simulation. Energy Build 2014;68:786–98.
[96] Wei W, Ramalho O, Mandin C. Indoor air quality requirements in green building certifications. Build Environ 2015;92:10–9.
[97] Jin J-T, Jeong J-W. Optimization of a free-form building shape to minimize external thermal load using genetic algorithm. Energy Build 2014;85:473–82.
[98] Vitruvius MP. The Ten Books on Architecture, republished and translated by Morris Hicky Morgan. 1960.
[99] Zawidzki M. Retrofitting of pedestrian overpass by Truss-Z modular systems using graph-theory approach. Adv Eng Softw 2015;81:41–9. https://doi.org/10.1016/j.advengsoft.2014.11.004.
[100] Zawidzki M. Deployable Pipe-Z. Acta Astronaut 2016;127:20–30. https://doi.org/10.1016/j.actaastro.2016.05.023.
[101] Zawidzki M, Nishinari K. Shading for building facade with two-color one-dimension range-two cellular automata on a square grid. J Cell Autom 2013;8.
[102] Zawidzki M. Emergence in the modular shading system based on cellular automaton. Adv Build Energy Res 2015;9(2):280–92.
[103] Zawidzki M, Bator M. Application of evolutionary algorithm for optimization of the sequence of initial conditions for the cellular automaton-based shading. J Cell Autom 2012;7.