GEOMETRY, GRAPHICS AND DESIGN IN THE DIGITAL AGE

The 9th International Scientific Conference on Geometry and Graphics

MONGEOMETRIJA 2023

Editors

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The 9th International Scientific Conference on Geometry and Graphics

MoNGeometrija 2023

June 7-10

Novi Sad, Serbia

Title of the proceedings

Geometry, graphics and design in the digital age

Publishers

Faculty of Technical Sciences, University of Novi Sad

Serbian Society for Geometry and Graphics SUGIG

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Print

GRID, Faculty of Technical Sciences

Number of copies:

10

ISBN

978-86-6022-575-9

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Serbian Society for Geometry and Graphics

International Society for Geometry and Graphics

Faculty of Technical Sciences

Digital Design Center

SUPPORTED BY

Provincial Secretariat for Higher Education and Scientific Research

Ministry of Science, Technological Development and Innovations

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AUTOMATED COMPOSITIONS: ARTIFICIAL INTELLIGENCE AIDED CONCEPTUAL DESIGN EXPLORATIONS IN ARCHITECTURE

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Abstract

The paper focuses on the challenges of the relationship between architecture and artificial intelligence (AI), in particular, the potential of this technology to support architects' creative design processes in the form of augmented intelligence. Conceptual architectural design is an intricate process that produces new concepts by using prior knowledge, experience, intuition, and creativity. Artificial intelligence should not be used during the conceptual design stage with the goal of solving a problem in a predefined search space. Instead, potential solutions and design requirements should be explored using this technology. The suggested approach avoids preconceived solutions and psychological inertia attributed to the designer's finite experience. The paper gives a brief critical review of the application of AI in an architectural context, especially in conceptual design. The review emphasizes changes in the design process brought about by cutting-edge strategies, methods, and tools based on AI. Further, research by design is presented to illustrate the possible use of biologically inspired algorithms in producing innovative design proposals. The applied strategy in architectural design production was based on the human-machine interface and interaction (HMI&I). Symbiotic human-machine interaction in the design process facilitates the emergence of automated compositions that display novel and unexpected forms, detail, materiality, structure, functionality, and aesthetics. This study allowed us to explore peculiar architectural design methodologies and the potential of digitally intelligent architecture.

Keywords: architectural design, generative design, design strategies, augmented intelligence, bio-inspired computing, human-machine interface and interaction

1 INTRODUCTION

The relationship between architecture and artificial intelligence (AI), and especially the ability of this technology to support architects' creative design process in the form of "augmented intelligence," is currently being reviewed by various authors [1], [2], [3], [4], [5]. In this context, augmented intelligence refers to a type of hybrid intelligence that combines human and artificial intelligence with the goal of supporting their strengths while reducing their weaknesses, enhancing both human and machine capabilities [6]. This paper also discusses modifications made to the design process due to cutting-edge AI-based strategies, methods, and tools, as well as various ways AI is used in conceptual design research in architecture. Through presenting case studies of different conceptual design explorations on automated compositions in architecture using AI principles, tools, and logic, the paper examines how human-machine interface and interaction (HMI&I) could be achieved in the creation of architecture. Examples illustrate how AI and HMI&I can be used to avoid pre-generated solutions, an architect's psychological inertia, and the promise of digitally intelligent architecture.

The term "concept" is often defined in the literature as an idea, representation, scheme, plan, system, figure, symbol, prototype, paradigm, abstract object, mental representation, description, solution, or proposal [7]. Conceptual research in architecture represents a dynamic process that produces new ideas using the author's previous knowledge, experiences, intuition, and creativity [8]. Forming an architectural idea is one of the most critical steps in the entire process of design development. On the other hand, the relationship between design and design tools in the creative process is bi-directional [9], and digital technologies have changed how architecture is taught, practiced, managed, and regulated [10].

The relationship between architecture and AI is a phenomenon that has been around for a while. It can be traced back to the 1960s when architects Christoph Alexander and Cedric Price used cybernetics to visualize the flows and dynamics of the development of design problems. While architects like Nicholas Negroponte specifically turned to AI to develop a system that becomes smarter over time, learning from its users and developing in symbiosis with them [11]. Digital technologies and algorithms, such as simulated annealing and genetic algorithms, are frequently used in contemporary architectural design practice to examine the concepts of optimally organized building plans, evaluate and optimize the static performance of light structures at the lowest possible cost, and find the most effective architectural solutions to improve the thermal, light, and other performances of the object [12]. In recent years, especially since 2015, there has been an increase in the number of published scientific papers on using AI to solve conceptual problems in architecture [8].

AI is a phenomenon for which there is an intense interest in the scientific, academic, and professional public at present, although there is no generally accepted definition for it [13]. The first time that the term Artificial Intelligence had been used was at a conference in Dartmouth College in Hanover in 1956. by John McCarthy [14]. Attempts were made in defining AI in information systems research, which resulted in more than 20 different definitions of AI by various authors in the field [15]. Rai et al. [16] define AI as the ability of a machine to perform cognitive functions that are usually associated with the human mind, such as perceiving, reasoning, learning, interacting with the environment, problem solving, decision-making. The four main properties of AI are most often referred to, namely: perception of the environment (with all the complexities it possesses), information processing (collection and interpretation of input data), decision-making (by reasoning and learning, reacting to changes in the environment, solving tasks), and achieving specific goals (which is considered the ultimate purpose of the existence of intelligent systems) [13]. European Commission has classified the main domains and subdomains of AI [13]. Following this taxonomy, the paper concerns topics of machine learning, natural language processing, computer vision, multi-agent systems, and robotic and automatization.

The use of AI allows for a wide range of solutions to problems defined after establishing the initial concept and re-evaluating project requirements. Starting from the premise that AI should not be used during conceptual design research in order to obtain ready-made solutions for inadequately researched problems, the goal of this research is to investigate how AI can be used in the process of developing architectural concepts and discover the domains in which this technology can be beneficial as a design tool. The research tasks are to provide a critical view of the use of AI in architecture, specifically within conceptual research, and to illustrate the possibility of using biologically inspired algorithms in producing innovative design proposals.

A multiple-case study research methodology was used to examine AI as a design tool in architectural concept explorations. Projects included in the study through research by design examine the creation of automated compositions. Conclusions about the way and domains of the use of this technology in the design concept development are formed based on the review of relevant previous research and the analysis of four case studies in which AI is applied to support the design of the architectural form, functional organization, performance, and operation.

2 FRAMEWORK

Technological growth in architecture was accelerated throughout the 1940s with the introduction of new construction concepts, i.e., the use of modular and standardized elements and mechanical mass production, which could be found in the work of architects Le Corbusier, Walter Gropius, and Buckminster Fuller. In the 1960s, the very first computer-aided design concepts debuted, such as Sketchpad, Urban 5, and Generator; since then, digital tools have constantly been developing, resulting in today's advanced computer-aided design (CAD) software like *AutoCAD* [2].

In the 1990s the digital revolution made a shift in architectural theory and practice. This progression of digital tools led to new architectural tendencies; parametricism and computational design rose in popularity, changing the way many architects viewed the design process. At this time, during the early 2000s, architecture saw the adoption of 3D modes of representation led and popularized by the works of architects such as Frank Gehry [17]. The move to 3D representation methods allowed designers to produce free-form spaces with new geometric complexity and depth levels. From this point on, new digital tools and their usage in architecture have rapidly developed. With the increasing number of tools, the main directions of software development for architectural digital representation are (1) Computer Aided Design (CAD), (2) Building Information Modelling (BIM), and (3) Algorithmic Design (AD) in which architects create descriptions of the design using algorithms [18]. Recent research shows the effectiveness of combining different software such as visual programming tools (*Grasshopper* and *Dynamo*), together with BIM technologies such as *Revit Architecture*, *Digital Project*, *ArchiCAD* and *Tekla* [19].

In the early 2010s, parametricism in architecture reached a standstill in both theoretical and technological terms as a result of concerns within the field that this approach would be overly strict and straightforward for the design process [2]. At the same time when the parametric design started to get criticized, the architectural practice became increasingly preoccupied with free-form structures that tested the potential of parametric design tools, AI learning systems, based on neural networks that derive solutions from raw data, started to gain popularity as they opposed the expert based parametricism. Thus, to overcome the disadvantages of parametric modeling, AI has emerged as a new design tool with the potential to mitigate some of the disadvantages of parametric design by implementing inherently digital logic in the design process [1].

2.1 Artificial Intelligence in Architecture

AI started developing in the 1950s as a result of the interest that the scientific community had in the concept of machine logic created as an imitation of the human brain. The concept of AI developed from cybernetics systems which can learn how to grow and reproduce [11].

Having in mind that there is no universal definition of AI, the questions of its operationalization in the legal, economic, and strategic domain rise. The European Commission's Joint Research Centre gave a taxonomy of AI by researching phenomena found in most scientific publications [13]. The importance of this technology can be seen in the fact that many countries worldwide, such as the UK, France, Germany, Finland, Scotland, China, Japan, and India, are developing national strategies for regulating the role of AI in public institutions and services. The city of New York published an *official Strategy for Artificial Intelligence* in 2021 [22].

In the field of architecture, the ways in which intelligent systems have been utilized can be seen through the prominent researchers in this field. The main themes in this discipline, which was named *Architectural Intelligence*, include Material Intelligence (main authors: Mike Xie, Philippe Block, Lyla Wu), Swarm Intelligence (main authors: Alisa Andrasek, Jose Sanchez, Karl Chu, Paul Coates, Cecil Balmond Roland Snooks, Ed Keller), Artificial Intelligence (main authors: Ian Goodfellow, Stanislas Chaillou, Wanyu He, Hao Zheng, Daniel Bolojan, Matias del Campo, Guvenc Ozel), Augmented Intelligence (Joi Ito) and Cyborg Intelligence (main authors: Andy Clark, David Chalmers) [23].

AI in architecture is still in its experimental development phase, where its potential is being researched, despite having a history of over half a century. Several papers deal with the usability of deep learning networks and computer vision for measuring the similarities between architectural projects based on gathered photographs [24]. Other domains in which AI is researched are using variable autoencoders to optimize the form of the building for its optimal thermal performance to create a performance-driven design [25]. Several papers question the role of AI in architecture and search for problems and potential to overcome those problems at the intersection of these two disciplines (e.g., [26]). Some authors found that AI can be used in conceptual research in architecture through design exploration, morphogenesis, building shape exploration, ceiling form design, facade design, and floor plan organization [8]. Several authors create artificial neural networks as form-finding tools that generate 3D object forms in vector format, trained on the data derived from existing buildings or given parameters [12].

2.2 Human-Machine Interface in Architecture

Engineer Douglas C. Engelbart introduced the concept of an *augmented architect at work* as a part of his report on augmenting the human intellect. In the report, he mentioned the upgrade of human intellect with the purpose of enhancing its capacity to approach complex problems, comprehend how to achieve certain requirements adequately, and increase its ability to solve specific issues [27].

According to Nicolas Negroponte, *architectural machines* are a dynamic design process in the form of a dialogue between humans and machines [11]. The concept of architectural machines is symbiotic at its core: it involves the intimate relationship between two different species (humankind and machines), two distinct processes (design and computing), and two different systems of intelligence (the architect and the architectural machine) [11]. The idea of improving human capabilities in the architectural field can be seen in the development of the digital tools that are used for design.

Steven Coons had a significant impact on ways of thinking about design and architecture from the very beginning of CAD. Under Coons' direction, CAD Project engineers not only created the ground-breaking CAD technologies but also theorized creativity and representation in terms of computation, envisioning a collaboration of humans and computers working together indexing various types of information. In addition, he shifted the research focus for CAD toward innovative forms of interaction and augmentation instead of automating design [28].

This study examines the interaction between humans and machines by analyzing designers' various uses of digital and AI tools and models for developing architectural concepts during pre-concept and other initial phases of design. Respectively, several types of human-machine interaction are mentioned, including 2D and 3D presentation, parametric design, simulations, environmental technologies, building construction technologies, and programming (coding and scripting) [29].

3 STUDY

The task of the study is to analyze the generative potentials of AI tools and the HMI&I approach in architectural design. The study includes four cases with a common project design task. The spatial and programmatic framework of the design projects involves an intervention at the location of the former Federal Ministry of Internal Affairs building in Kneza Miloša Street in Belgrade, which was destroyed in the NATO bombing in 1999.

The study reviews diverse applications of AI in architectural concept formulation and visualization. Starting from distinct designers’ interests and design intentions, cases illustrate AI-aided architectural design explorations of diverse building aspects, including form, functional organization, performance, and operation. Each case represents the application of distinct design methods and computational tools in producing innovative designs. Respectively, the potentials of AI text-to-image tools (such as *DALL-E* and *MidJourney*) are tested in the context of design form explorations; Information Maximizing Generative Adversarial Networks (InfoGAN) are instrumentalized in explorations of the functional organization of building’s typical units. Conversely, other biologically inspired algorithms were applied to assess the building’s performance evolution, and the concept of automated building operation was experimented with using Cellular automata.

The qualitative and comparative analysis summarizes the basic methods of conceptual research for each case, types of input and output data, applied software packages, the type of intelligence used, the stage in the concept development in which the support of AI was included, as well as the types of HMI.

3.1 Cases

3.1.1 Case 1: Design Formation

The design focuses problem of extreme urban conditions that are recovering from the aftermath of manmade or natural crises. It represents a reaction to the collective trauma caused by the destruction of war. The design intends to open the way of healing and space for social dialogue through the recognition of trauma and memory. The project raises questions about what architects can learn from studying conditions in their most fragile, raw, and unstable state and what architects might potentially contribute to crises in the aftershock of conflict or natural disasters. At the same time, the project investigates the relationship that architectural design might have with the urban rubble of reality at a time when the dominant cultural tendency in architecture education and cutting-edge practice is oriented towards exploring virtual design environments supported by the human-machine interface and interaction (HMI&I).

The design intention was implemented through a specific creative process in which an AI system based on the Constructive Language-Image Pre-training (CLIP) model was applied as an embedded system that supported design conceptualization and form explorations. Similar to the "zero-shot" abilities of Generative Pre-trained Transformer 2 and 3 (GPT-2 and 3), CLIP is a neural network that effectively learns visual concepts from natural language supervision and can be applied to any visual classification benchmark by merely providing the names of the visual categories to be recognized. This type of algorithm is based on computer vision technology, and its role is to translate textual descriptions into 2D representations [30]. The CLIP model consists of two sub-models called encoders: (1) a text encoder that will embed text into mathematical space and (2) an image encoder that will embed images into mathematical space. The text and image encoders are fitted to maximize "goodness" and minimize "badness," just like in any supervised learning model.

The design process started with extensive field research on the buildings destroyed during the NATO bombing in 1999. One of the goals of this research was to verbalize people's collective trauma caused by distractions in the city. Formulated text descriptions were exploited to generate a series of digital images using the AI system *DALL-E* [31]. Unlike some other computer vision techniques, this AI system has the advantage of using already-created images and captions, requiring far less additional human labeling effort. Already-labeled data, along with generalizability, speed, and accuracy, makes this tool appropriate for fast explorations at the outset of the design process. Although the machine generated numerous quality visualizations, digital images further went through the iteration of interpretation, manual alterations, and collaging to set in meaning (Fig. 1).

Fig. 1. Visual explorations in the phase of design formation using AI text-to-image tool (Studio M01 – Spatial Structures: Automated Compositions, class student Marija Arsić, University of Belgrade – Faculty of Architecture 2022/23)

The task of the following phase was to translate 2D images obtained through HMI&I into a 3D model of the spatial structure, which proved to be a challenging task, as previously noted by some authors [1]. Several approaches were tested, including the translation of the 2D collages into the building's facades using the *Image Sampler* component in *Grasshopper* as well as the translation of 2D visualizations in the 3D model via Blender software package. However, these experimentations did not give satisfactory design results. Therefore, in the continuation of formal explorations, 2D images served as an outline for spatial form explorations using a marching box computer algorithm [32] for extracting a polygonal mesh of an isosurface from a 3D discrete scalar field. The algorithm was implemented in *Grasshopper*, the visual programming editor for the system for parametric 3D modeling *Rhinoceros*. Using this aggregation tool – custom marching box script, a high-resolution skyscraper structure was generated from the elements representing parts of destroyed buildings.

In this project, the destruction of the city fabric with unfathomable ecological consequences is opposed by the attitude towards optimal use of resources, regeneration, and creation of a healthy environment. The 119m skyscraper would be constructed using reprocessed materials and original parts of damaged buildings. Another outcome of previous fieldwork was a sustainable systematic proposal for converting post-bombing waste into raw materials, reformed materials, and a bank of reusable building elements. The building is designed as adaptive and (re)usable civic space and space for tertiary institutions that support economy and livelihood. This attitude towards building function and materialization contributes to considerations related to the flow of resources, circular potentials of the built environment, and reuse/rebuild/recycle technologies in architecture. As a result of this experiment in regenerative design and HMI&I-based formation, a skyscraper of expressive shape, detail, materialization, construction, and aesthetics emerged.

3.1.2 Case 2: Design Organization

The design reviews the quality of housing in Belgrade from the aspect of the contemporary user needs within the city in constant adaptation to the changing population density conditions. Starting from the critique of the current housing production, the design exploration aims to offer proposals that will answer the challenges of social sustainability and quality of life (QOL) demands. Furthermore, in the emerging era of industry 5.0, when human intelligence coexists with cognitive computing, the project investigates whether such cooperation can result in the creation of customized, human-centric designs as opposed to solutions that are driven by the market.

With machine learning, the organization design of an apartment unit plan was automated in this project. Previous research was conducted using a type of Generative adversarial network [33] – infoGAN [34] for training deep convolutional models for generating synthetic images extended to introduce control over the generated image (e.g., style, thickness, and type in case of generating images of handwritten digits). With InfoGAN, the discriminator model that determines whether a picture is real (based on the training dataset) or fake (generated) is trained alongside the generator model for creating images. As a result of the two models' zero-sum competition, achieving convergence during training requires striking a compromise between the generator's ability to produce convincing images and the discriminator's capacity to recognize them.

In order to provide input data for the training algorithm, the starting point of the design process was a study of the apartments in Belgrade, with a focus on apartments from the second half of the XX century (the 1970s and 1980s). Selected 2D floor plans used for training neural networks previously went through the process of redrawing to unify graphic presentation. InfoGAN has the task of generating plans for new apartments based on the input information and according to a set of rules. Generated output data indicates what kind of apartment units provide comfortable living. To generate quality solutions, it is necessary to form an extensive and diverse database. The type of information initially defined in the analysis of the basics of apartments is the size and function of the rooms in the apartment, as well as their number. Outputs are also classified based on size, function, and the number of rooms. The matter of data for training algorithms is a sensitive topic for both technical and ethical reasons. One of the main challenges in using generative adversarial networks is the database size required to obtain quality results, which range between 10,000 and 50,000 images. The potential of using GAN technology when designing an architectural object is represented by analytical insights into potential solutions for the set criteria and the author's dialog with the generated solutions (Fig. 2)

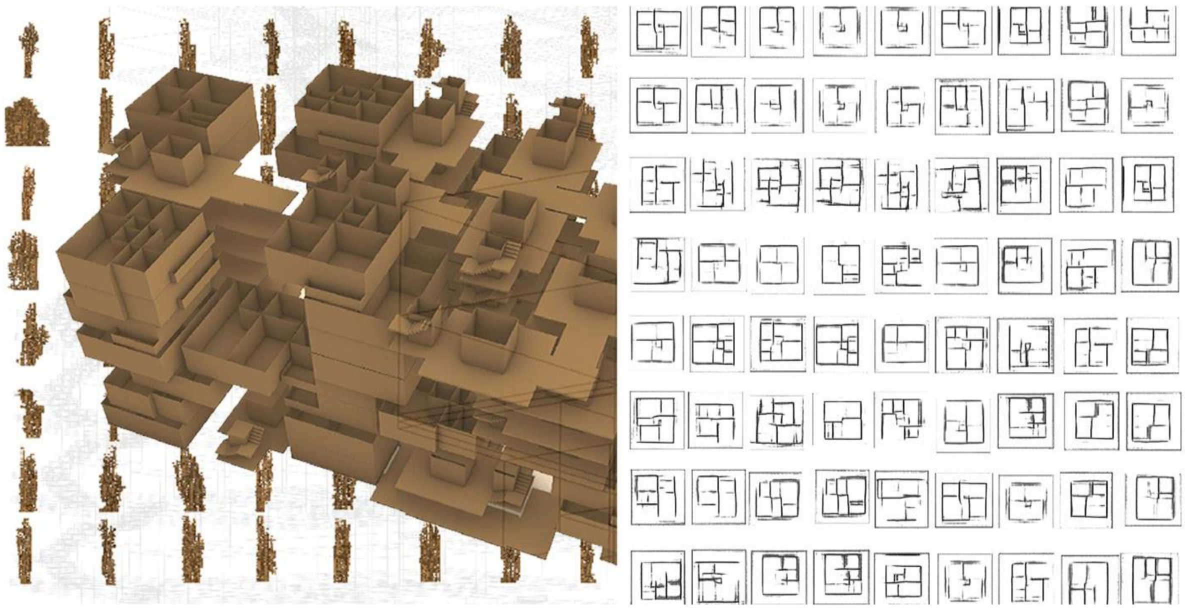

Fig. 2. Generated unit apartment plans using infoGAN and building aggregations (Studio M01 – Spatial Structures: Automated Compositions, class student Jelena Stevanović, University of Belgrade – Faculty of Architecture 2022/23)

In the next stage of the design process, generated 2D plans were extruded into 3D apartment units using the *Rhinoceros* modeler. Spatial apartment units served as modules (building parts) for generating spatial aggregations using graph grammar stochastic compositional algorithms by applying defined compositional rules (connections between modules) and constraints. This algorithm was implemented using the *Wasp* plug-in [35] for *Grasshopper*. The shape of the building results from a form-finding process in which bottom-up computational generative procedures that produce modular aggregations are combined with top-down modeling strategies based on the introduction of external constraints, including the effects of insolation, wind, and vision (Fig. 2). The ecological value of the building and QOL were additionally promoted using timber post and plate structural system and materials with low CO2 emissions.

Combining lessons from the analysis of apartment design in the second half of the XX century with contemporary people's needs, social sustainability, and QOL demands resulted in an innovative design proposal for a high-rise residential building with a certain extent of the comfort of individual housing. Previous step was challenging because, in order to use the space most efficiently, tall buildings' design sometimes causes a loss of focus on the user and his social aspect. The flexible spatial organization and distribution of contents balance users' needs for individual, shared, and common spaces while spontaneously encouraging connectivity, socialization, and the creation of community relations. Considering changing societal and production circumstances due to technological development and the digital economy, spaces are designed to ensure social, physical, and psychological well-being. Application of the AI algorithm reduces architects' repetitive work saving time for creative tasks, and along with the proposed application of automated construction technologies, gives a hint at the potential of digitally intelligent architecture.

3.1.3 Case 3: Design Performance

The study questions the design of environmentally responsive high-rise buildings with improved performances. The building represents a research center for nuclear and alternative forms of energy as a response to the global energy crisis. The facility is metaphorically located on the site of a building destroyed in the NATO bombing in 1999, during which explosive devices containing depleted uranium were used. Through this project, the destruction of unfathomable ecological consequences is opposed by a concept oriented towards the optimal use of resources, a regenerative approach, and creating a healthy environment.

The design intention was to create a transformable tall building that changes its form in accordance with the environmental conditions using AI. The design intention was realized through envisioning of moving elements on the building in the form of capsules/cells that can be rotated around the axis of the building, as well as brisoleils on the facade that rotate in accordance with the direction and intensity of air flow, in order to transform the building into an intelligent building that reacts to its environment, adapting and creating optimal configuration. These AI managed building transformations are envisioned as responses to the wind conditions and should provide optimal natural ventilation. In order to ensure occupant comfort, several additional aspects must be considered very early in the building design because the performance of naturally ventilated systems is strongly reliant on the geometry of the building and the weather conditions. Previous challenge asked for a specific design approach.

The design intention was realized using generative and performative design strategies and digital tools for form-finding and predictive mechanisms. *Wasp*, a *Grasshopper* [35] plug-in that provides combinatorial tools for designing with discrete elements, was used for form-finding. In this case, discrete elements used for aggregation represent the building's functional units in the form of capsules/cells. Possibilities of aggregation of a capsule with other capsules are defined with the connections, the topological graph of the capsule. A stochastic aggregation procedure was applied within the constrained design space, allowing geometry-driven structure generation to be applied. Performances of generated designs were then evaluated using Finite Element Analysis (FEA) and Computer Fluid Dynamics (CFD) simulations. Performance evaluation results were used as feedback information and for design modifications and improvements in the iterative process.

This heuristic design process is functionally equivalent to big data [36]. Modern science, and specifically the field of structural calculation when it comes to buildings, has seen a revolution in concepts and methods as a result of our access to previously unimaginable computing capacity. Respectively evolutionary algorithm (EA), as bio-inspired computing algorithms that use mechanisms inspired by nature and solve problems through a process that emulates the behavior of living organisms, generally, can be applied to search solution space for optimal performance design based on the data obtained from FEA and CFD calculations. However, automating the design process through iterative design simulations utilizing an evolutionary solver, such as the *Galapagos* component in *Grasshopper*, proved to be a demanding task in terms of computational effort. The even greater challenge is to realize the concept, which involves the replacement of calculating predictions based on mathematical laws and formulas by the search for a precedent for the case we are trying to predict, retrieve it from the almost infinite, universal archive of all relevant precedents that ever took place, and replace it.

The approach to the design of intelligent buildings dates back to the time of Generator, a project developed by Cedric Price from 1976 to 1979, representing a model of distributed intelligence in built form ([11], p. 147). One of the concepts explored in the domain of intelligent buildings is active structures, for which there is a parallel with the physical-kinesthetic intelligence of man. This type of building often has automatic doors, windows, or elements on the facade, such as brisolei, that move according to weather conditions ([37], p. 44). Drawing on those predecessors, design utilizes current technological capabilities to create a transformable spatial structure, adaptable as a response to information on structural performances and wind effects, in a symbiotic relationship with its environment (Fig. 3).

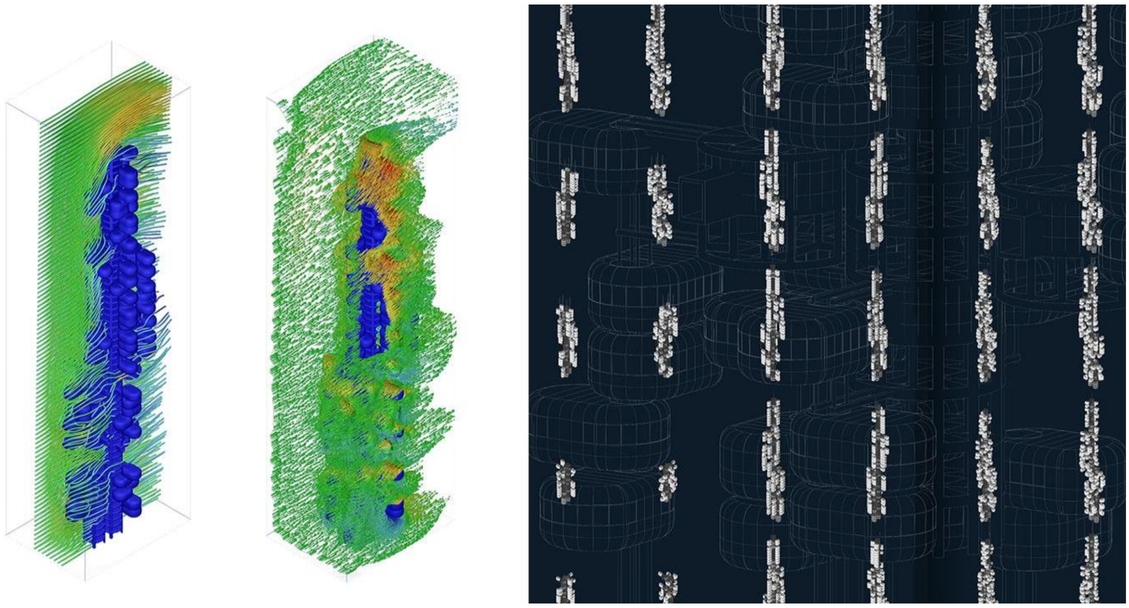

Fig. 3. Design variations and an example of the CFD analysis of a design alternative (Studio M01 – Spatial Structures: Automated Compositions, class student Danilo Ćorković, University of Belgrade – Faculty of Architecture 2022/23)

3.1.4 Case 4: Design Operation

The project deals with the current problem of dense stationary traffic and the disproportionate ratio between the number of vehicles and parking places in Belgrade by designing a typical public garage with integrated intelligent systems that would dynamically manage the organization of cars. Furthermore, project hypotheses for how this facility might be used and operated in the future when the traffic system is based on autonomous vehicles (robocars) that can move without human input once technology develops, AI is capable of operating properly in chaotic inner-city environments, and moral concerns are resolved.

The project researched the idea of anthropocentric human-less architecture in the form of an automated storage system within the high-rise building layout based on the machine and their needs. The project idea is supported by Object-oriented ontology (OOO), a school of thinking influenced by Heidegger that rejects the privileging of human existence over the existence of nonhuman objects [38]. Hyperobjects are another philosophical concept behind the design [39]. In relation to humans, hyperobjects are massively distributed items in both time and space. They are referred hyper in relation to some other entity, whether created by humans or not. Respectively, the aim of this project, which focused on automation as a hyperobject, was to suggest a workable future scenario based on current reality and a new high-rise building design strategy that is no longer human-centered but rather machine-centered.

Considering previous ambitions, the scenario of the building's operation was a first step in the design process. Technological advancements contribute to the compression of not only data [10]. Furthermore, a study from the University of Toronto on the optimal size of the grids where driverless cars park themselves demonstrates more efficient use of space [40]. When it is added that parking lots for autonomous vehicles would not require space to open the doors, walkways, elevators, or staircases for people, those savings become even more pronounced. Nevertheless, the success of compression is backed by the superiority of search methods over conventional sorting methods [10]. Machines do not have queries on the meaning and do not need taxonomies, labels, sort classify, or another type of organization to make sense like humans if the efficient search algorithms support them. For example, Amazon has an unorganized warehouse in which they tag and track using RFID. The previous brings us to the scenario of building operation in which quantity (of vehicles) is effortlessly done through a simple query reflecting on building operation.

The building operation was simulated using the cellular automata (CA) algorithm [41]. In this project, CA consists of a regular three-dimensional grid of cells representing parking lots. Each cell has a finite number of states on (the place is taken) and off (the place is free). Then the set of rules that define and update the state of cells in relation to their neighborhood over time is defined and applied to the spatial grid simultaneously. The algorithm was implemented using custom *Grasshopper* definition that generates 3D cellular compositions using components of the *Rabbit* plug-in [42]. This definition facilitated the representation of potential solutions coming from the spatiotemporal evolution of the starting cell arrangement over time (Fig. 4).

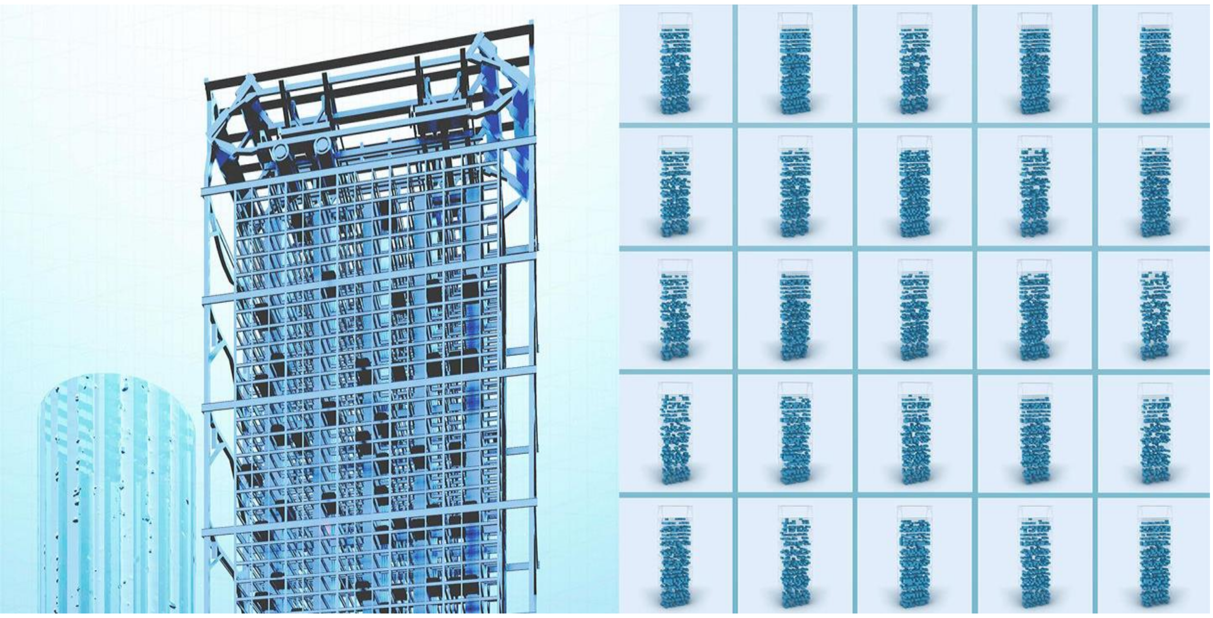

Fig. 4. Automation of the high-rise building operation using cellular automata algorithm (Studio M01 – Spatial Structures: Automated Compositions, class student Anja Boltić, University of Belgrade – Faculty of Architecture 2022/23)

The proposed construction technology further supported the evolution and autonomous growth of the capacity, which implies the application of a 3D printer for large-scale in-situ construction of the building's space frame. The massive frame supporting the 3D printer was designed using a topology optimization algorithm and does not only represent the design motive but points to the potential of automation in construction (Fig. 4). Contrary to the full automation of building construction and operation, the design process includes application of several digital tools. It represents a dialogue between the designer and the machine, which achieves dynamics in the research of how the building can satisfy the needs of non-human users.

3.2 Analysis

The criteria for qualitative comparative analysis derive from the observation of the main challenges faced by the authors of the presented cases and relevant authors from the literature dealing with related topics. The specificity of the four considered cases is represented by the fact that the designers did not have previous knowledge or experience using certain AI algorithms. The final criteria for case analysis include a review of the initial design intention/idea, the conceptual research phase in which the AI-based tool or model was used, the type of applied AI tool, the type of input data, the type of obtained data, and the type of interaction between the human (architect) and machines (computers). The results of the analysis are summarized in Table 1.

Table 1. Comparative qualitative analysis of the four cases

Criterion	**Case 1** **Formation**	**Case 2** **Organization**	**Case 3** **Performance**	**Case 4** **Operation**
Design intention	regenerative design in the aftermath of disasters, including systematic proposal for the conversion of waste into building materials that has symbolic visual qualities	innovative typology of high-rise residential buildings designed in accordance with social sustainability and QOL criteria	environmentally responsive transformable high-rise building that provides optimal natural ventilation	prototype of machine-centered high-rise automated public car/robocar garage that efficiently uses space
Role of AI in realization of design intention	generation of visual Inspirations related to buildings form that will guide further form explorations	generation of new apartment floor plans	form optimization and regulation of building's configuration based on performances due to the wind effects	optimal functioning of the building and simulation of spatiotemporal scenarios
Applied AI generative system	text-to-Image generator	InfoGAN code	stochastic aggregation and EA solver	CA solver
Designers additional work on AI based generative system	no additional work use of open-source application	creation of script	creation of custom code	creation of custom code
Input data for AI supported generation	textual description of the concept	2D apartment floor plan drawings	geometry data: 3D module geometry connection rules, constraints data on weather conditions	3D grid of cells, cell states, rules that define and update cell states
Output data of AI supported generation	2D images	2D images of generated floor plans	3D models of aggregations – environmentally responsive configuration	3D models of cell arrangements over time

Post phase of AI supported generation	extensive work on interpreting and transforming of results into spatial model second stage of generative process based on application another generative system	extensive work on selecting results transforming results into spatial model second stage of generative process based on application another generative system	additional manual work due to the impossibility of effective implementing EA solver to manage big data	minor additional work

4 CONCLUSIONS

The paper addresses some of the areas and applications of AI in the conceptual stage of architectural design, emphasizing changes in the design process brought about by cutting-edge strategies, methods, and tools. Current development of the technology opens diverse possibilities for creation based on HMI&I expanding current generative design strategies with intuitive design approaches based on an even greater degree of cooperation, intuitive problem-solving, and intuitive tools based on the implementation of biologically inspired algorithms and machine learning. Outcomes of these collaborations show that designs may have improved either overall or particular performances in addition to their striking visual effects.

The four case studies presented in this paper test distinctive design methodologies which embed specific AI tools with the goal of participating in the development of a particular building's aspect – form, organization, performance, or operation. Some principles underlying applied technologies, including neural networks, generative adversarial networks (GAN), computer vision (DALL-E), natural language processing (DALL-E), and cellular automata (CA), relevant for understanding their role in the design process are briefly presented. In all cases, design processes include previous explorations, description of design intentions, domains, and constraints, design exploration based on HMI&I, and outcomes assessment. In all cases design process was only partly automated, various digital tools were included in the process, and substantial designer work was done on the interpretation and modification of results. While computational tools contributed to the processing of a large amount of data, fast production of alternatives and generation of a far greater number of variations, the designer's knowledge, perception, intuition, and experience were crucial for interpretations, revisions, and adjustments of results. Augmented intelligence realized through the symbiosis of human designer and machine, when employed in the conceptual phase of the creative process, as illustrated in the study, can contribute to the emergence of designs with amplified qualities.

A brief review of the relevant literature shows that although the relationship between AI and architecture is currently a popular topic, there still needs to be more studies concerning the creative application of the technology in the conceptual design phase. While technology demonstrates its superiority in performance-based design focused on improving specific technical performances, in the future, much more research effort needs to be directed toward innovating architectural design methodology and tools to find effective ways of employing technology that will be consistent with the nature of the creative processes.

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