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Original Research Article

Development of Algorithmic Applications in Architecture :A Review and Analysis of L-Systems*

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Abstract

Problem Statement: L-systems are among the algorithms for calculating the self-organized process of "environmentally sensitive growth" of plants. They are one of the five main generative methods that, given the structure and main field of application, promise great potential in architecture. But at the same time, examples of their application in architecture are few and have not yet been sufficiently developed. Therefore, their development requires a comprehensive study. So, in this study, while identifying the possible potentials in architecture, the background of their applications in architecture as well as in other fields are reviewed. Then, these applications are divided and compared, and accordingly, some suggestions for development are presented.

Research objective: The purpose of this research is to comprehensively investigate L-systems and identify their applications and potentials in architecture.

Research method: This article is descriptive-analytical, and the data collection method is documentary-based. The documents used in this article include a variety of articles, books, dissertations, and architectural competitions, all or part of which is related to research on architectural applications and other related applications of L-systems that have been published since 2000.

Conclusion: Exploring the algorithm in the field of botany, the five main concepts of L systems are: development, abstraction, self-similarity, complexity in simplicity, and topology; Among these, the concept of development is more popular in architecture, while other concepts have received less attention. In this regard, reviewing their applications in other fields and their methodologies will be inspiring. In this article, research trends in the architectural applications of the L-system are identified and the reasons for its decline in recent years, as well as suggestions for development, are presented. Other analyses are also presented, including the scientific validity of the documents used, the types of applications, the methodology of the L-system, and the design stage.

Keywords: *L-systems, Self-similarity, Topology, Abstraction, Development, Algorithmic architecture.*

Introduction and Problem Statement

With the advent of computers and the identification of natural structure algorithms in the last century, these algorithms entered other fields of science. Meanwhile, computational approaches in biology had special relevance for computer-aided

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architectural design because they used generative grammars for form generation (Marinčić, 2019). L systems, which were introduced in 1968, are one of the algorithms for calculating the self-organized process of environmentally sensitive "growth" of plants and one of the five main generative methods (Mountstephens & Teo, 2020). These systems, in addition to generating branching structures that are their most famous potential, have concepts in their structure that can be very interesting to architects and provide new solutions for design problems. Since no comprehensive review study has been done on L-systems in architecture, this study investigates these systems. So, this article tries to provide an overview of the background, concepts, classification of applications, and introduction of their potential in architecture.

The first step to discovering the potential of this algorithm in architecture is to analyze it in the main field, i.e., the biology of plant growth. Therefore, the second part of this article introduces this algorithm. In the third part, architectural applications and applications developed in other fields that can be developed in architecture are divided, reviewed, categorized, and compared in a table. In the fourth part, the practical concepts of L-systems in architecture are extracted, and the data related to these applications are analyzed and reviewed. In the end, the main points are summarized, and suggestions for future research are presented.

This article seeks to answer the question of what are the applications of L-systems in architecture, what potentials can be imagined for them in architecture and how can they be developed? Three hypotheses govern this research: First, L-systems have a lot of potential to be used in architecture and design. Second, analyzing the algorithm in the main context and having a conceptual vision can help develop these applications. Third, reviewing and investigating the applications of these algorithms in other fields leads to the development of their applications in architecture.

Research Method

This article is descriptive-analytical, and the method of data collection is documentary. The documents used in the introduction of L-systems include research and review articles, and in the applications section, it includes all kinds of research articles, theses, as well as top architecture competitions. The main keywords include generative design, L-systems, procedural content generation, fractals, growth patterns, branching morphogenesis, and several other keywords. The time limit for the search was considered from 2000 onwards. Many documents containing the desired keywords were found, but most of these documents include only a review of L-systems, which were removed from the sources of this article. In the applications of L-systems in other fields, it is enough to mention several examples, but due to the limited research articles about these systems in architecture so far, almost all of them have been mentioned in this study.

L-Systems

Modeling growing biological systems with a self-similar structure, such as plants, has many complications, including changing the components of the organism and changing its neighbor relationships. Aristide Lindenmeier, for this purpose, proposed the L-systems grammar and then developed it to simulate more complex structures, including the structures of trees, leaves, buds, etc. (Prusinkiewicz, Cieslak, Ferraro, & Hanan, 2018).

L-systems include two main parts: a generative process and an interpretive process. The generative process of an L-system includes three main parts:

• V (alphabet): sets of symbols that include components that can or cannot be moved (Ibid.). Symbols of the alphabet in an L-system represent the distinct units (internodes, leaves, flowers, etc.) of the growing organism (Mishra & Mishra, 2007).

• ω (start, axiom, or initiator): strings of N characters and variables from the set V that defines the initial state of the system.

• P: P is a set of production rules or productions defining the way variables can be replaced with combinations of constants and other variables. Production consists of two parts, the left-hand side: the module to be replaced, and the right-hand side: the module which is replaced (Mikkelsen, 2020).

The main concept of the generative process is rewriting, in which the constituent letters and the initial string are replaced in parallel by new letters according to predetermined rules. This string rewriting process is usually repeated several times (Prusinkiewicz et al., 2018). One of the most important potentials of these systems is the ability to create complexity with little data because an initiator and a few production rules are its only input data.

Up to this point, L-systems are just a tree structure of data, without appearance and geometry (Fig. 1). In the second part, the letters of the last generation of strings are interpreted. It means that it is possible to study the visual interpretation of strings as geometric forms (Prusinkiewicz et al., 2018).

Therefore, different interpretations of L-systems have been proposed as a post-process step (Mishra & Mishra, 2007). One of these geometric interpretations is the turtle graphic. The general concept of this method is that an imaginary turtle in a two-dimensional or three-dimensional space is able to move in different directions, can turn at different angles, and it can also return to its previous position, and return to continue to move and rotate (Fig. 2) (Prusinkiewicz et al., 2018).

Therefore, L-systems perform two main tasks: representing (packaging) information in symbols and interpreting those symbols as growth patterns (Alfaris, 2009). The strings produced by L-systems can be interpreted as topological maps, i.e., neighborhood relations and connection patterns between cells or larger plant modules (Prusinkiewicz et al., 2018). The most famous ability of L-systems is their ability to develop branching structures (Lane, 2015). However, L-systems should not be defined only as generators of tree-like geometric objects. The topological approach in modeling, inherent in L-systems, has also inspired research and the establishment of practical methods for modeling growing cellular layers and volumetric structures (Lane, 2015). Therefore, according to

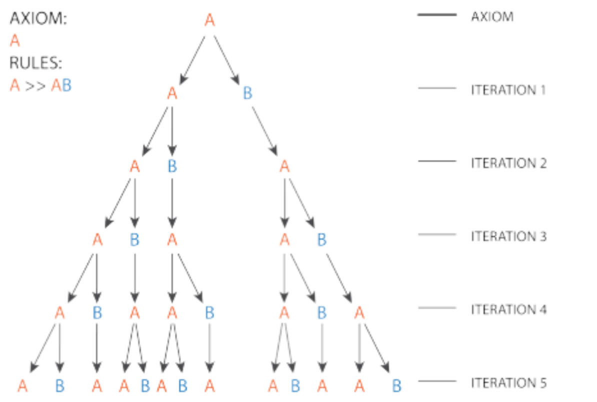
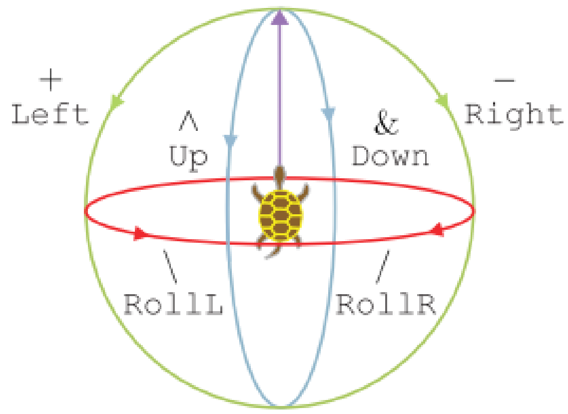


Fig. 1. In the first stage, L systems are only a structure of data. Sourc: Österlund, 2013.



Turtle command	Symbol	L+C Keyword
Draw line segment	F	F
Move without drawing a line	f	f
Turn left | right	+ | -	Left/Right
Bend up | down	^ | &	Up/Down
Roll to the left |right	/ | \	RollL/RollR
Start |end branch	] | [	SB/EB
Set line width	#	SetWidth
Set line color	,	SetColor

Fig. 2. Turtle rotation in three dimensions and the main commands of turtle graphics. Source: Prusinkiewicz et al., 2018.

the abstraction and metaphor in the structure of the L-system, its capabilities can be used with newer methods. (Prusinkiewicz et al., 2018).

- **Variations**

L-systems can be deterministic or non-deterministic and stochastic (by adding probability distribution functions, etc.), context-free or context-sensitive (dependence of the growth of parameters on the previous and subsequent modules), and parametric (adding numerical parameters and conditions to the structure) or non-parametric, each of which has specific applications (Mishra & Mishra, 2007).

- **L systems in plant modeling**

In modeling plants with L-systems, it is possible to act at several levels, 1) cellular, 2) other plant components such as leaves and buds, 3) overall plant structure and so-called plant architecture, or 4) in plant communities and interactions resulting from competition for light, space, etc.

One of the important potentials of L-systems is their ability to model environmental effects. In these models, the key morphogenetic role in plant growth is assigned to self-organization due to the competition between branches for space, light, gravity, etc. (Runions & Prusinkiewicz, 2012). Researchers developed L-systems in a way that is suitable for simulating the interactions between a plant and its environment, which can even model pruning and the effect of different seasons (Taylor-Hell, 2005). One can model a plant and randomly apply environmental effects to it to create plants with different appearances (Prusinkiewicz et al., 2018).

Sometimes the modeling process is done in reverse. The problem of finding the L system of a given type for a set of observations is called the 'inference problem' for that type. In fact, the problem of L-system inference is to find an L-system to simulate a certain plant (McQuillan, Bernard & Prusinkiewicz, 2018).

To accurately simulate these processes, due to the inherent limitations in the formalism of L-systems, various extensions and combinations of L-systems have been proposed. The best solutions proposed so far are the combination of L-systems with programming languages such as C/C++, Java, and Python (Prusinkiewicz et al., 2018). Most of these combinations have been made to increase the speed and reduce the volume of data, simplify the programming and make it possible to model more complex structures (Taylor-Hell, 2005).

The most important combination of L-systems with evolutionary algorithms, including genetic algorithms, is to evolve structures based on fitness criteria and functions. Mathematical models of L-systems are generative; therefore, their complement is a variety of evaluation and optimization methods. In using genetic algorithms in order to evolve L-systems, a basic model of L-systems is usually considered, and then its evaluation criteria are determined, and the structure is started with genetic operators such as mutation, combination, or crossover. Genetic operators can be applied to seeds, rules, number of iterations, and turtle interpretation, producing different results (Mishra & Mishra, 2007).

L-systems in Architecture

L-systems have many applications in different fields. In this article, with a comprehensive review of authentic articles and documents, the applications of L-systems in architecture and other fields are divided into seven sections (Fig. 3), and after the introduction of each of them, the relevant examples are presented in a table for comparison.

Fast modeling with details: Fast modeling with details or in other words, procedural content generation and modeling are among the important applications that use the ability to generate complex structures with few parameters of this algorithm and has been well developed in urban planning and computer games. Procedural modeling tools expand basic information according to a specific algorithm and automatically generate complex 3D models from an input seed just by following a small set of rules (Coelho, Sousa & Ferreira, 2020). In the game industry, due to the need for a large amount of high-quality content, an acceptable level of control, a small volume of data, and diversity in the generated structures (Risi & Togelius, 2020), this method has recently been used. For example, Antoniuk used developed L-systems to create spaces for computer

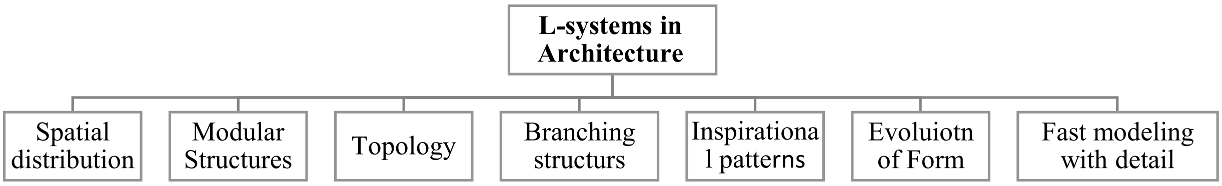


Fig. 3. Classification of applications of L-systems in architecture. Source: Authors.

games with the aim of diversity in plan design (by observing other features such as symmetry, the necessity of having two small and large spaces, etc.) (Antoniuk, Hoser, & Strzęciwilk, 2019), (Fig. 4).

In urban planning and archeology in recent years, L-systems have been used to model urban spaces quickly with a small volume of data or to create different styles of urban architecture (Wonka, Aliaga, Müller & Vanegas, 2011) and produce an urban environment that can develop quickly. Severe reduction of input data and self-similarity are important characteristics of L-systems in this application and can be considered in architecture. Also, L-systems are used in new methods of modeling road networks and communication ways, the main purpose of which is the development and growth of an interactive algorithm that matches the characteristics of a scene and the input environment. (Fig. 4). This approach can be inspiring in creating architectural concepts based on environmentally-sensitive movement paths.

In a few cases, procedural techniques based on L-systems have been used in architecture to model complex forms (Lorenzo-Eiroa, 2013), of which no valid document was found, but it can be found in student works, which is not discussed in this article.

Evolution of form: In order to evolve the form in architecture, it is possible to use the combination of L-systems with evolutionary algorithms. Such a system allows two types of evolution. Interactive selection, based on human perception, allows the user to direct the simulated evolution towards preferred shapes and subjective and aesthetic criteria (McDermott et al., 2012). In another method, automatic evolution is simulated using a genetic algorithm with clear fitness functions and defined mathematical relationships (for objective criteria). Therefore, through an iterative process of selection by the user and genetic operators by the computer, the resulting forms can be optimized (Goos & Hartmanis, 2004).

The combination of L-systems and genetic algorithm in architecture has been proposed since the 90s and the few works done in different fields of design, industrial design, aerospace, etc. are: Coates et al. in functional design in architecture and introduction of single-objective evolutionary methods (Coates, Broughton & Jackson, 1999), Coates et al. in the CECA Institute to develop an architectural form by combining L-systems, genetic algorithm and swarm intelligence (to define the fitness function) (Coates, Appels & Simon, 2001), Jackson in developing pseudo-architectural structures and investigating interactive evolution and subjective preferences of users, multi-objective methods and also proposing a co-evolutionary approach (Jackson, 2002), Hornby and Pollack in aerospace to examine the benefits of coding with generative grammars for evolutionary design (Hornby & Pollack, 2001) and (Hornby, 2004), Tang in developing the co-evolutionary approach (Tang, 2005), Popovici, in order to evolve a family of designs to reach the desired response (Popovici, 2005), Narahara in architecture to investigate random 3D geometries using parametric L-systems with turtle interpretation and then evaluating these structures with the help of multi-objective methods and weighted functions (Narahara, 2010), Kiptiah et al. in engineering to investigate the hybrid framework between the interactive genetic algorithm and the L-system and define user preferences in creating three-dimensional structures (Kiptiah Binti Ariffin, Hadi & Phon-Amnuaisuk 2017, 2017), (Fig. 5) and Saleri, who in part of his research has mentioned the ability to

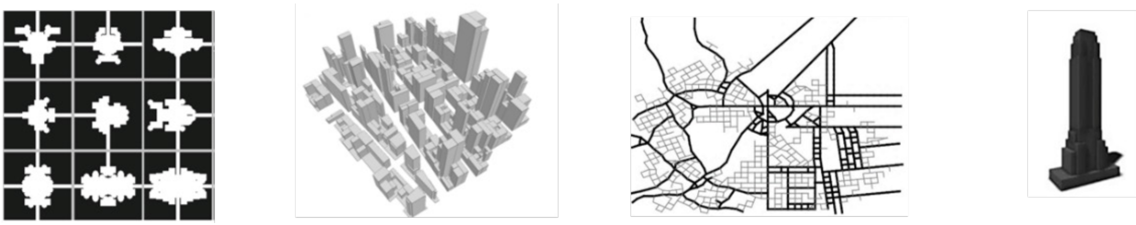


Fig. 4. Application of L-systems in fast modeling with details in different fields. From left to right: game industry, urban planning, road network design, building facades modeling. Source: Authors.

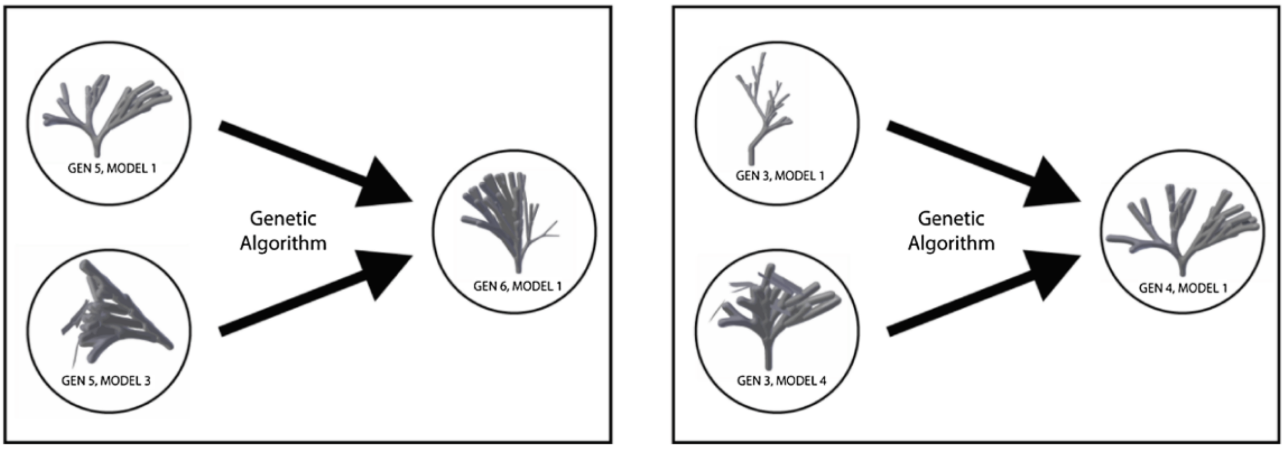


Fig. 5. The combined system incorporates preferences of paretns' 3D models to a new child model. Source: Kiptiah Binti Ariffin et al., 2017.

combine these two algorithms and create functional objects in architecture (Saleri, 2020). It should be noted that this part of the applications, despite its high potential, has not produced a significant product in architecture and has focused more on examining the ability of these systems to produce geometric objects. Therefore, the researches are in the early stages and need more studies.

Grammatical evolution, which is a genetic programming technique, is used in combination with L-systems, and the most important result in architecture is the Genr[8] surface generation tool, in which three-dimensional digital surfaces with organic quality grow in response to a simulated environment that mimics the environmental influences such as gravity and sunlight (Fig. 6), (Ryan, O'Neill & Collins 2018).

Patterns: The patterns that L-systems create can be inspiring in architecture, and these systems are a very interesting tool for generative art and abstract patterns (Fig. 7), (Romero & Machado, 2008). These systems can start from patterns with a simple geometry in the first iteration and become more complex with each iteration. Some of these patterns, which are the result of the recursive and self-similarity structure of the algorithm, are fractals, and almost all fractal designs can be drawn with L-systems (Shiffman, 2012). Another approach is to apply simple geometric operators to patterns created by L-systems.

Branching structures and geometries: Branching structures generated with L-systems can be environmentally sensitive or not (Fig. 8), which is the most famous application of L-systems in architecture as well as other fields. In the architecture of branching structures with L-systems, plugins such as Rabbit and ARMy Ant have been published, each of which has different capabilities but needs to be developed for more purposes.

Regulating component relationships: Topology, according to its mathematical definition, is the study of intrinsic and qualitative characteristics of geometric forms that are not normally affected by changes in size or shape. Topological

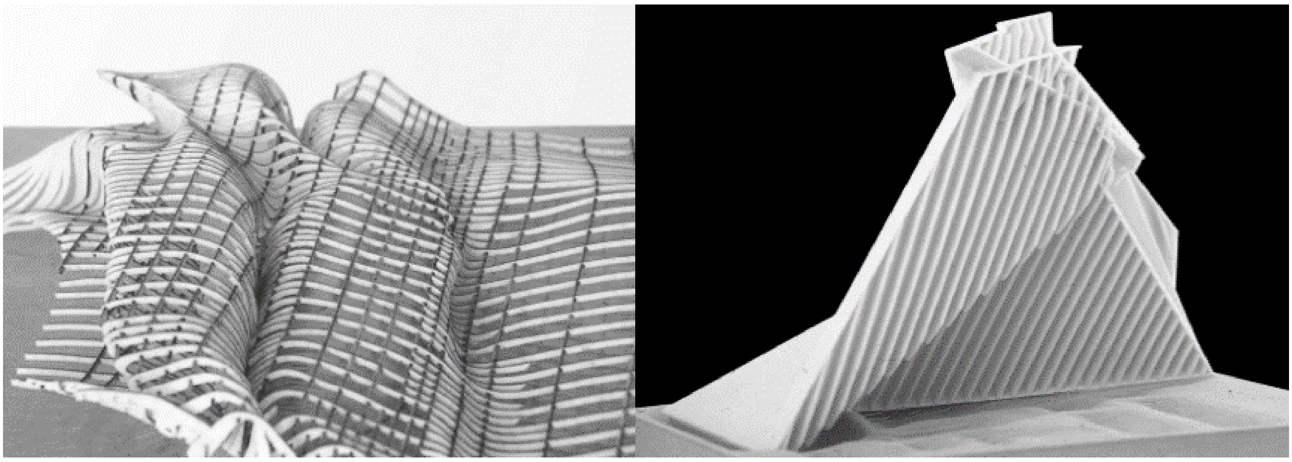


Fig. 6. Surfaces generated with the GENR8 tool developed with the concept of L-systems. Source: Ryan, O'Neill & Collins 2018.

Fig. 7. L systems in generating patterns (from right to left): interactive art - creating geometric structures with simple geometric operators - fractals. Source: Shiffman, 2012.

Fig. 8. An example of branching structure generated with L-systems. Source: Morphocode.com.

transformations, first of all, affect the relational structure and, therefore the resulting form(s) (İçmeli, 2013). L-systems, which have topological concepts in their structure, can efficiently regulate the relations of components. For example, the adjustment of component relationships can be used in an abstract way to adjust the connections between the architectural plan spaces, guide and adjust the heat distribution, or optimize the topology of a structure.

L-systems have been used in recent years, especially in the field of topology optimization in aerospace engineering. Topology optimization in structural and mechanical engineering means finding the optimal distribution or design of materials in a certain area by observing the limits and boundary conditions in order to maximize the performance of the system (Kobayashi, Pedro, & Hude, 2010). Among these, we can mention Kobayashi et al. in the optimization of flapping mechanism and airplane wing structure, Khetan et al. in the optimization of the topology of trusses in structural engineering (Khetan, Lohan & Allison, 2015), Hartl et al. in the design of deformable truss structural structures (Hartl, Reich & Beran, 2016), Kearney's Ph.D. thesis at the University of Hawaii in 2015 in the optimization of aircraft wing structure (Kearney, 2015), and MIKKELSEN's master's thesis at the University of Texas In 2020, in the design of the topological layout of the primary structure of the helicopter rotor blade section (Mikkelsen, 2020), (Fig. 9).

Optimizing the topology of architectural structures is very practical, and there are different approaches and methods for it that are still being developed. According to the content presented in this section, the new methodologies of using L-systems in topology optimization can also be inspired by the development of new approaches in architecture. Topology can also be defined in heat conduction and distribution. For example, Ikonen et al. (Ikonen, Marck, S´obester & Keane, 2018) used parametric L-systems to optimize the multi-objective topology of heat conduction to minimize the average or maximum temperature to distribute a limited amount of high-conductivity materials (Fig. 10). Such an application can be used in the development of optimal heating and cooling systems and architectural concepts based on it in large spaces, and one can use approaches based on L-systems that have been recently developed in this field.

Another example of regulating relationships of components is in modeling building spaces, which is used in urban planning and graphics to use available data and infer the L-system, and finally modeling (Peter, 2017) and reproducing spaces. For example, it has been used in an article to document the internal condition of the building and prepare "as-built" maps for large and public buildings that have higher-level rules such as symmetry and repetition (ibid.). In another article published by Becker et al. in 2013, by combining the concepts of L- systems and split grammar, the automatic modeling of communication spaces (corridors) inside buildings from sensor data is developed (Fig. 11). (Becker, Peter, Fritsch, Philipp, Baier & Dibak, 2013). Such an idea can be used to find a family of designs. That is, after getting the data from the sensors in a building with a specific use, all kinds of possibilities for creating internal plans based on the behavior of users are examined, and the design question is defined as "optimizing a plan based on the user's movement paths". Based on this, the desired L-systems are deduced and similar structures are generated and finally, the best designs based on the design goals are selected.

In another article presented by Fernando and Drogemuller in 2015, the concept of topology is used in plan design, and it is stated that beyond period and style, buildings can be grouped by

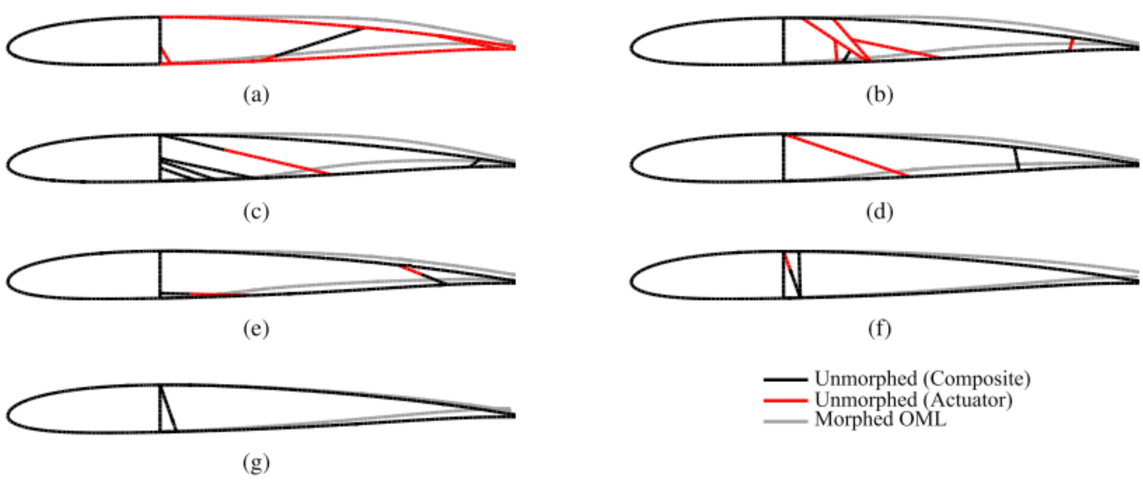


Fig. 9. L-systems application in the design of topological layout. Source: MIKKELSEN, 2020.

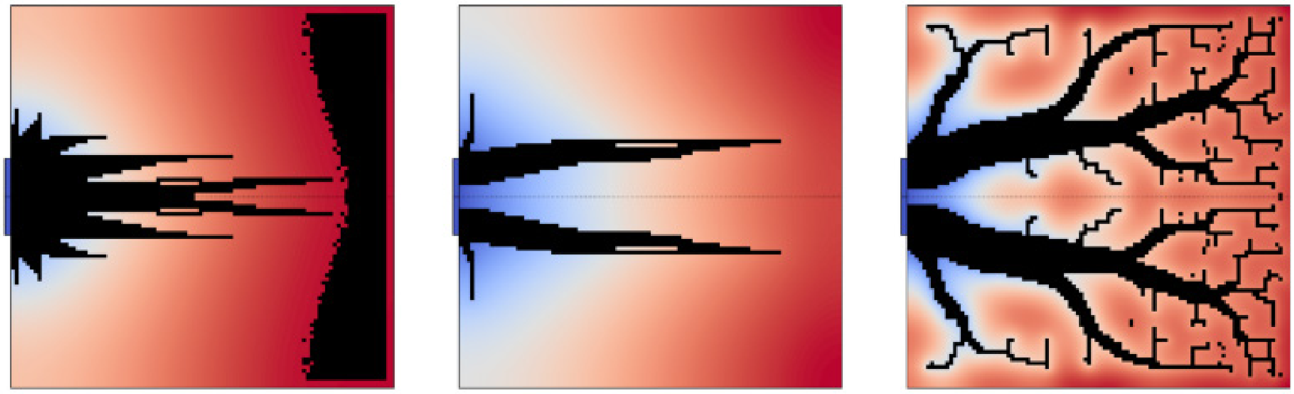


Fig. 10. Heat distribution design with parametric L-systems. Source: Ikonen et al., 2018.

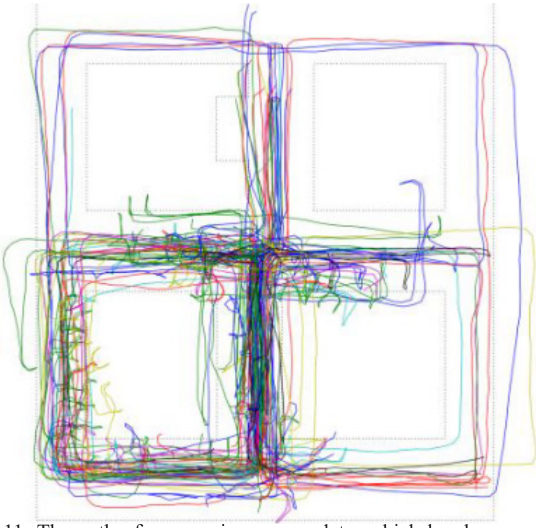


Fig. 11. The path of users using sensor data, which has been used to redesign the plan by inferring the L-system. Source: Becker et al., 2013.

focusing on their underlying structure (i.e., topology). They used L -systems to metaphorically represent the morphology of a spatial layout in a cellular network and invented GL-systems (Fig. 12), (Fernando & Drogemuller, 2015). This example is the only application of this concept that is done specifically in architecture and has a lot of potential for development. For example, the structural units that make up the building plan can be considered as a unit of the area, and relations and topology can be defined for this building unit that will create interesting results in the plan.

As can be seen, there are few examples of this application of L-systems in architecture, but it has been more developed in other fields.

Modular structures: Another application of L-systems is to use them in modular structures. The alphabet of L-systems is multiplied in the growth of the algorithm structure, and as a result, it is repeated in the whole structure, and for this reason, it is a suitable algorithm for modular structures. There are a few examples of modular structures generated by L-systems that can be seen in Hansmeyer's works and some student projects (Fig. 13), (Петрушевски, Деветаковић & Митровић, 2010), (Gorgora.de, 2011), (Kniemeyer, Barczik, Hemmerling & Kurth, 2008), (Kahn, 2008).

Spatial distribution: The last application observed for L-systems is in environmentally sensitive spatial distributions, which also have a few examples. For example, Bessa promoted positive phototropic responses of a generative process for the distribution of residential units (Bessa, 2009), (Fig. 14). In another case, L-systems have been used as a generative organizational design tool to design a university campus master plan in an abandoned industrial area (Diniz, 2012).

In Table 1, articles and research documents related to these applications are presented. In this table, which is the result of a detailed study of L-systems applications in different fields and their methodology, an attempt has been made to summarize and compare the most important relevant points.

Discussion and analysisUsing modern: mathematical and logical concepts is a unique challenge in all fields of design. L-systems are certainly one such concept that is theoretically well-defined. In this

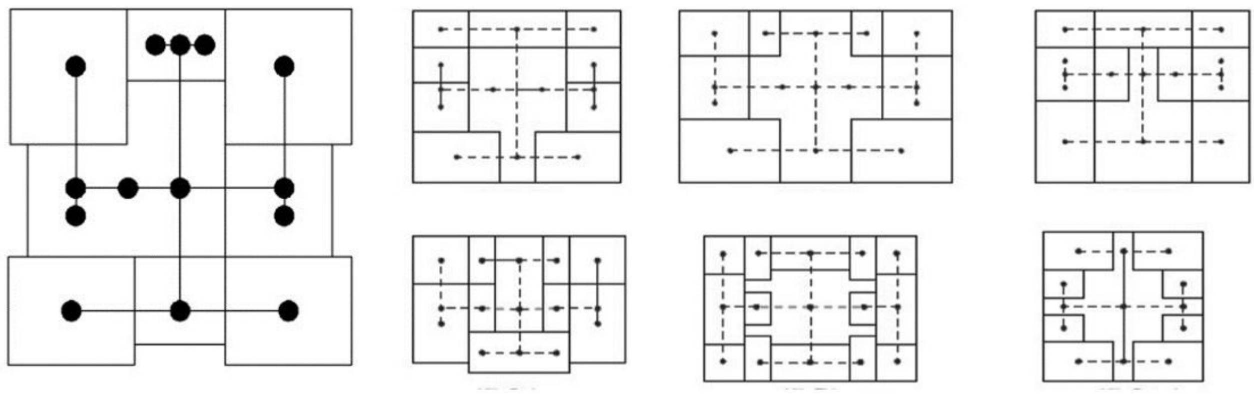


Fig. 12. The only research that specifically deals with topology in architectural design. In this system, plans with similar topology and connections can be produced and expanded in a fraction of the time. Source: Fernando & Drogemuller, 2015.

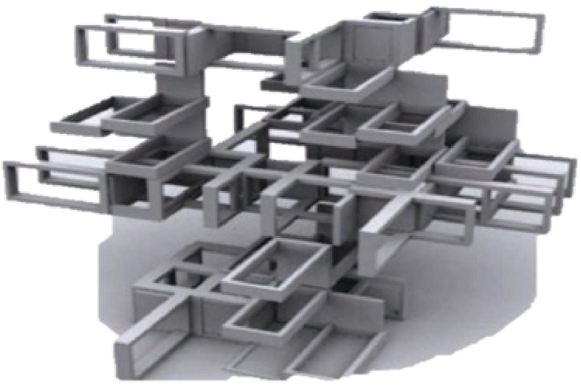


Fig. 13. A sample of student work in Russia. Source: Петрушевски et al., 2010.

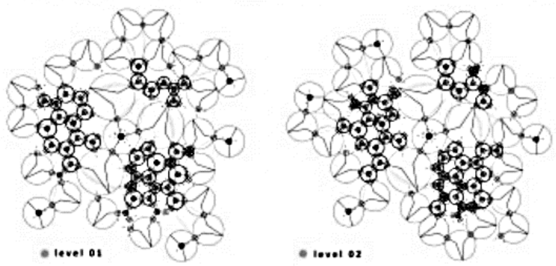


Fig. 14. Distribution of residential units using environmentally sensitive L systems. Source: Bessa, 2009.

article, the structure of the algorithm was examined in the main field, and its concepts and potential were extracted from specialized articles on plant growth modeling. According to the contents of section 2, and with the detailed study that was done in this research on the structure of L-systems, the concepts and potentials of L-systems in architecture can be summarized in Table 2. Each of the concepts creates different potentials, some of which are developed in architecture and some are not developed. So, it is necessary to take steps toward their development by considering these concepts. In Table 1, the scientific documents used in this research, based on which the applications of L-systems are determined, are presented. In this table, the mentioned scientific documents are organized in the order of time, and the type of reference, area of expertise, main purpose, application of the L-system, the method used, the concept of the L-system that is emphasized, and the stage of its use in the design are stated. The concepts used in these articles are extracted based on inference from the methodology of the document or an explicit mention. Almost all the documents used are research documents, except "branching structures" in some cases. In some cases, the application of the L-system is only a part of the document and is not the main subject. Also, in this article, the documents of the applications of L-systems in other fields are presented only to familiarize with the purpose and method. Therefore, numerical analysis is not done on these articles, but this information has been used in other analyses. The distribution of the scientific documents used in this article on the "architectural application of L-systems" are as follows based on the time of publication (Fig. 15). These documents have been published since 2000.

As can be seen, during the years 2001 to 2010, a lot of research has been done in this regard in architecture, which was mainly in AA School of Architecture in London and Massachusetts Institute of Technology, and as a result in other universities and research centers. In the meantime, the Genr[8] plugin, which is a powerful conceptual tool for simulating the

Table 1. Classification, comparison and analysis of the applications of L-systems in architecture and other related fields. Source: Authors.

Source	Type of Source	field	Main goal	application	l-sys approach	concepts	Design phase
(Coates et al., 1999)	Book chapter	architecture	Definition of combined methodology with L-system in form evolution	Evolution of form	Combination of genetic algorithm with simple L-system	Abstraction/development	concept
(Coates et al., 2001)	Conference proceeding	architecture	Development of hybrid methodology with L-system	Evolution of form	Combination of L-system, genetic algorithm, and swarm intelligence	Abstraction/development	concept
Parish & Müller,) (2001	Conference proceeding	Urban planning	Development of combinational L-system methodology for urban space modeling	Fast modeling with detail	Developed L -system (proposed by the authors)	Development/self-similarity/topology/complexity in simplicity	modeling
Hornby & Pollack,) (2001 (Hornby, 2004)	Conference proceeding and Journal article	Aerospace	Examining the benefits of combining generative grammars in evolutionary design	Evolution of form	Combination of genetic algorithm with L- system	Development/Topology/Abstraction	concept
(Jackson, 2002)	Book chapter	Architecture	Investigating the potential of combining L- system and genetic algorithm	Evolution of form	Combination of genetic algorithm with L- system	Abstraction/development	concept
(Dollens, 2005)	book	Architecture	Development of branching structures in organic architecture	Branching structures	Environmentally sensitive L- system	Development/self-similarity	concept
Landreneau, Ozener,) Pak, Akleman & Keyser , (2006	Book chapter	Architecture	Production of architectural plans in an interactive platform	Inspirational patterns	Applying geometric operators on patterns and fractals	Development/self-similarity	concept
Marvie, Perret , Perret,) (2005	Journal article	Urban planning	Modeling various building styles in urban space	Fast modeling with detail	Modified L- system	Development/self-similarity/topology/complexity in simplicity	Modeling
(Popovici, 2005)	Academic document	Computer-design	Evolution of a family of designs to achieve the desired response	Evolution of form	Parametric L- system with turtle graphics in combination with genetic algorithm	Development/Topology/Abstraction	concept
(Tang, 2005)	Conference proceeding	Architecture	Research in the co-evolutionary approach	Evolution of form	Combination of L- system and genetic algorithm	Abstraction/development	concept
Hensel & Menges,) (2006	Journal article	Architecture	Combining digital design and materials (creating Environmentally sensitive branching structures)	branching structures	Environmentally sensitive L-system by determining the range of parameters through experiment and growth	Development/self-similarity/topology	Modeling
(Hensel, 2006)	Journal article	Architecture	Description of system potentials L	-	Conceptual description	Development/self-similarity/topology	-
(Menges, 2006)	Journal article	Architecture	Polymorphism (combination of structure, materials, and form)	Evolution of form	generating growing surfaces with external forces and combining with the construction method (genr8)	Abstraction/development	Modeling and construction
Coelho, Bessa, Sousa) (& Ferreira, 2007	Journal article	Urban planning	Development of facade modeling methods and reduction of modeling bugs	Fast modeling with detail	L-Geospatial System	Development/self-similarity/topology Complexity in simplicity	Modeling
(Hemberg, 2001) Hemberg & O'Reilly,) O'Reilly &) (2004 (Hemberg, 2007 Byrne, Hemberg,) Brabazon, O'Neill Byrne,) (2012 Hemberg & O'Neill Hemberg, et) (2011 (al., 2007	book/journal article/dissertation-MIT/conference proceeding	Architecture	Development of environmental effects simulation software for the growth of surfaces	Evolution of form	Combining the L- system with the genetic algorithm (grammatical evolution)	Topology/abstraction/development	concept
(Pan, 2007)	eVolo competition	Architecture	The tree structure of tall buildings	Branching structures	Simple L-system	Development	concept
(Ei-Khaldi, 2007)	Master's Thesis/MIT	Architecture	Investigating how to combine 7 generative algorithms in architectural design	Branching structures	Simple L-system	Development/abstraction	concept
O'Neill & Brabazon,) (2008	Conference proceeding	Graphics - computer	Logo design	Evolution of form	Combination of L- system and genetic algorithm	Topology/development/abstraction	concept
Romero & Machado,) (2008	book	Computer-art	2D and 3D virtual painting	Inspirational patterns	Combination of L- system and swarm intelligence	Abstraction/self-similarity/development	final design stage
(Kahn, 2008)	Master's Thesis/University of Cincinnati	Architecture	A tall building with a branching structure	Branching structures	Inspiration from L-system in column growth with hybrid methodology	Development	Modeling
Kniemeyer et al.,) (2008	Book chapter	Architecture	Creating architectural drawings and objects	Modular structures	Relational growth grammar and grogra software	Development/self-similarity	concept
ydroponic-) (garden, 2009	Design competition	Architecture	Sustainable garden design with a branching structure	Branching structures	Simple L-system	Development	Modeling
(Menges, 2009)	Design competition	Architecture	The branching structure of a library building	Branching structures	Environmentally sensitive L- system	Development/self-similarity	Modeling
(Bessa, 2009)	journal article	Architecture	Distribution of residential units	Spatial distribution	Environmentally sensitive L- system	Development/abstraction	concept
(Jones. 2012)	Design competition	Architecture	design of the branching column of a restaurant	Branching structures	Simple L-system	Development/self-similarity	Design
(Arponen et al., 2009)	Book chapter	Architecture	Providing an alternative perspective in Finnish architecture with algorithmic methods	Branching structures	L-system with a branching structure	Development/self-similarity	concept
(Narahara, 2010)	PhD Thesis/Harvard University	Architecture	Presenting emergent architecture methodology	Evolution of from	Combination of parametric L- system with genetic algorithms and evaluation of structures with a multi-objective method and weight functions	Development/abstraction/self-similarity	concept
(Kobayashi, 2010)	journal article	mechanical engineering	Optimization of flapping mechanism and airplane wing structure	Regulating relationships of components	combination with evolutionary algorithm and optimization with a multi-objective method	Topology/complexity in simplicity	Detailed design

Rest of Table 1.

Source	Type of Source	field	Main goal	application	l-sys approach	concepts	Design phase
Gu, Singh & Merrick,) (2010	Conference proceeding	Architecture	Providing a computational framework for integrating generative design techniques	Evolution of from	Using the output of the L- system in the input of other algorithms and vice versa	Development/self-similarity/abstraction/topology	concept
Петрушевски et al.,) (2010	Unknown	Architecture	Providing geometric drawing with L- system	Modular structures	Creating tools for parametric modeling with L- system	self-similarity	concept
Hanafin, Datta &) (Rolfe, 2011	Conference proceeding	Architecture	Examining the branched structures of building facades	Branching structures	Simple L-system with turtle interpretation	Development	Modeling
(Diniz, 2012)	Conference proceeding	Architecture	Master plan design	Spatial distribution	Environmentally sensitive L- system	Development/abstraction	Concept
(Becker et al., 2013)	Conference proceeding	Information Technology	Automatic modeling of building spaces from sensor data	Regulating relationships of components	Combination of L- system and Split grammar	Topology/abstraction	Detailed design
Nordin, Hopf , &) (Motte , 2013	Conference proceeding	Industrial Design	Designing complex objects with a generative algorithm	Branching structures	generating branching structures in combination with a genetic algorithm with specific fitness criteria	Development/self-similarity	Concept
(Jormedal, 2013)	Master's thesis/ Linköpings universitet	Information Technology	Procedural modeling of road networks	Fast modeling with detail	Parametric L- system	Topology/self-similarity/complexity in simplicity	modeling
(Chu, 2014)	book chapter	Architecture	generating a family of topological surfaces	Inspirational patterns	Applying simple geometric operators on patterns	Development	Concept
(Kearney, 2015)	Ph.D. Thesis / University of Hawaii	Mechanics and aerospace	Optimizing the structure of the airplane wing	Regulating relationships of components	Combination of map L-system, genetic algorithm and cellular structures	Topology/complexity in simplicity	Concept
(Khetan et al., 2015)	journal article	structural engineering	Optimizing the topology of trusses	Regulating relationships of components	Map L-system and genetic algorithm	topology	Concept
Fernando &) (Drogemuller, 2015	Ph.D. Thesis/University of Queensland	Architecture	Using the concept of topology in plan design	Regulating relationships of components	Modified L- system – GL-systems	Topology/abstraction/development	Concept
(Hartl et al., 2016)	Conference proceeding	Aerospace	Designing deformable structures of trusses	Regulating relationships of components	L-system and genetic programming	Topology/complexity in simplicity/development	Concept
(Kiptiah et al., 2017)	Conference proceeding	Engineering - computer	Facilitating modeling of 3D objects with high control over the volume	Evolution of Form	L-system and genetic algorithms	Abstraction/development	Modeling
Soltanzadeh &) (Masnavi, 2017	Conference proceeding	Architecture	Using tree structures to design the columns of large spaces	Branching structures	Simple L-systems and genetic algorithm	Development/self-similarity	Detailed design
(Ikonen et al., 2018)	journal article	Engineering and design	Optimizing the multi-objective topology of heat conduction with the aim of minimizing the maximum temperature	Regulating relationships of components	Parametric L- system and genetic algorithm	Topology/complexity in simplicity	Concept
(Alnobani, 2018)	Master thesis / CMU University	Architecture	Adaptive geometric design framework	Regulating relationships of components	Simple L-system with hybrid methodology	Abstraction/development/topology	Concept
(Antoniuk et al., 2019)	Journal article	Computer games	Creating a diverse plan with a small volume in a computer game	Fast modeling with detail	Modified L- system	Development/self-similarity/topology/abstraction	Detailed design
(MIKKELSEN, 2020)	Master thesis / University of Texas	aerospace engineering	Designing the structural topological layout of the helicopter rotor section	Regulating relationships of components	Parametric L- system and SPIDRS algorithm	Topology/complexity in simplicity	Concept
(Saleri, 2020)	Book chapter	Architecture	Studying generative algorithms and evolutionary approaches	Evolution of Form	Combination of L- system and genetic algorithm	Abstraction	-
Sharp, Blay,) Kholodova & Correa (2021	Conference proceeding	Architecture	Façade design inspired by the movement principles of plants	Branching structures	Using the L- system as a starting point in the distribution of the facade cable structure	Development/Abstraction	Concept

Table 2. Concepts and potentials of L-systems in architecture. Source: Authors.

Development	Abstraction	Self-similarity	Topology	Complexity at the same time simplicity
Growth processes and emergent forms	Flexibility in the interpretation and production of types of geometry	Fractal patterns	Defining the relationships of system components	Emergent forms
Dynamic processes (with increasing components and relationships)	Combining with other algorithms and hybrid methodologies	Modular structures	Dynamic processes (with increasing components and relationships)	Simulation of self-organization
Combination with evolutionary algorithms and evolution of structures	Environmental effects	Patterns with golden proportions	Simulation of combined effects and their relationships	Reduction of inputs and high control over outputs
Possibility of process in reverse	Random structures, context-sensitive, time-sensitive, environmentally-sensitive		Simulation of environmental effects	Generating complex structures with small data volume
	Combination with evolutionary algorithms and evolution of structures			A compact description of 3d shapes

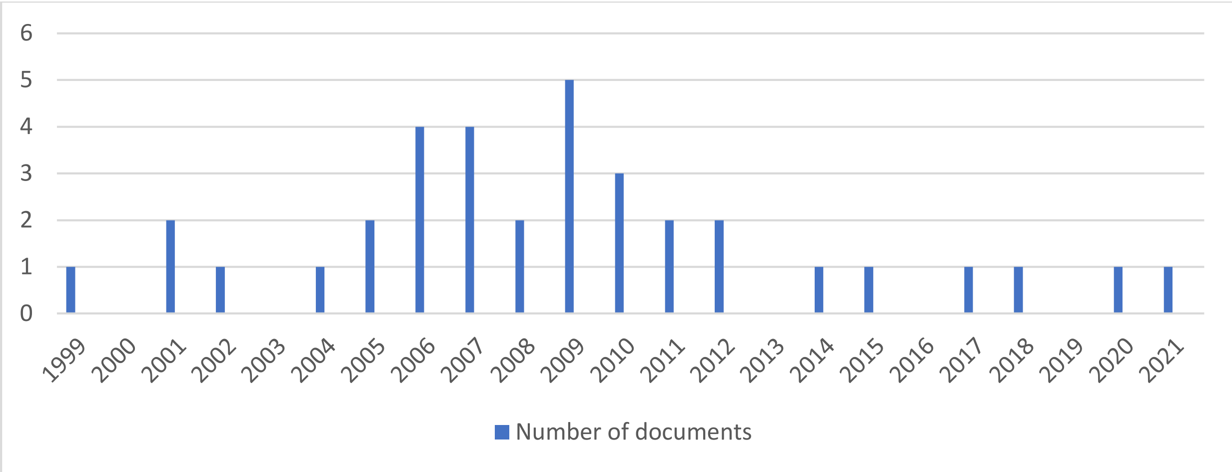


Fig. 15. Distribution of scientific documents on the application of L-systems in architecture based on publication time. Source: Authors.

growth of surfaces in architecture, was developed. Student projects focusing on these systems were also found in abundance in these years, which were not discussed in this study. Gradually, the pace of these studies in architecture decreased, but the development of L-systems continued with combined methodologies in other fields, especially aerospace, engineering, information technology, computer games, urban planning, etc. It seems that there are two main reasons for the decrease in the research about L-systems in architecture. First, these systems have their roots in biology, and the up-to-date articles related have entered the phase of complex mathematical calculations and combined methodologies, and architects may use them without having the correct conceptual model in a set of mathematical formulas and so get confused by not getting the desired results. While with the correct conceptual model and sufficient conceptual understanding, this algorithm is like a tool that is very simple to use, and at the same time, its results (either forms or processes) will be very complex, which is what the contemporary architect is looking for, and it is the point of view which is discussed in this article. The second reason can be the lack of comprehensive investigation and monitoring of other developments and applications and methodologies of these systems in other fields. Therefore, there is a need for articles and research that examine these systems with a more comprehensive and conceptual perspective and express their potential in a collection that is understandable for architects, which is the main goal of this article.Effective cooperation between the three experts of computer engineering, biology, and digital architecture in this field is an issue that should be considered. It is necessary to have a computer engineer to simplify the algorithms and their concepts and code the process, a biologist in the correctness of the conceptual model, and a digital architect to combine these ideas and define the application and solve problems in architecture. The Genr 8 plugin, which was considered significant development, was the result of such an effective collaboration between architects and computer engineers. In Fig. 16 the documents presented in Table 1 are distributed by type of document:

The articles are published and presented in prestigious journals and conferences, theses and doctoral theses are related to high-ranked universities (according to the table), and the books are published by reputable publishers, which shows the importance of the subject. The distribution of the studied documents based on the type of application in L-systems is as follows (Fig. 17):

The most common application of L-systems is “Evolution of form”, but the results in this part are not sufficiently applicable yet, So, the need for more research on the combination of L-systems

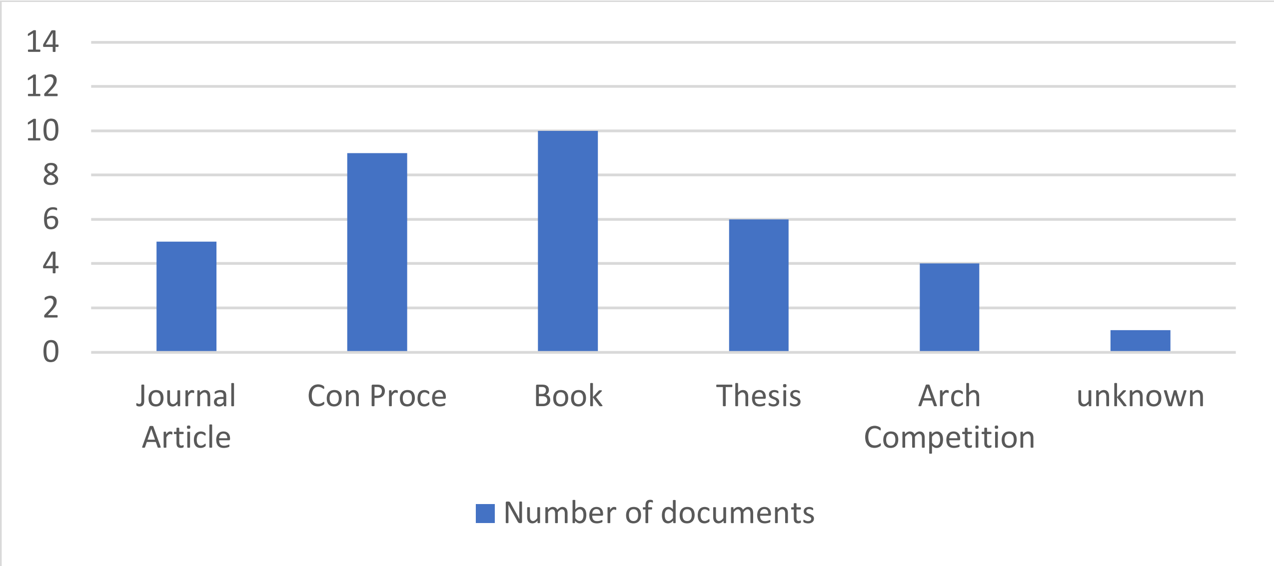


Fig. 16. Distribution of scientific documents of L-systems applications by type. Source: Authors.

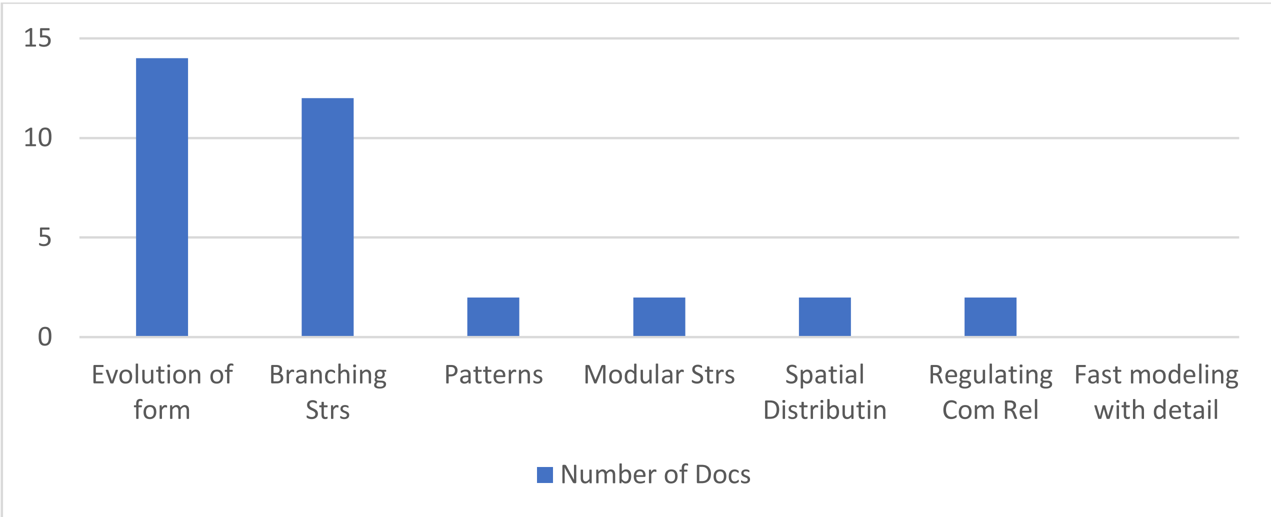


Fig. 17. Distribution of scientific documents based on the type of L-systems application of. Source: Authors.

with evolutionary algorithms is felt and can be the subject of future research. Branching structures are in second place because the most famous feature of these systems is the creation of branching structures, but at the same time, many cases are observed in student research. Other applications such as spatial distribution, modular structure, and patterns also have few published documents but are abundantly found in student works. In the fast modeling section with many components, there was no example in architecture. In developing the applications of this algorithm, researchers have paid attention to the concept of development and have worked more on creating complex structures similar to growth (Fig. 18). The "self-similarity" concept is less in published scientific documents, but it is abundantly observed in student works. While in the non-architectural applications of L-systems, the most emphasis is on the concept of topology and the regulation of component relationships, complexity in simplicity, and also abstraction. These applications that have been developed in recent years, need to give more attention in architecture, because:

The concept of topology: The design has

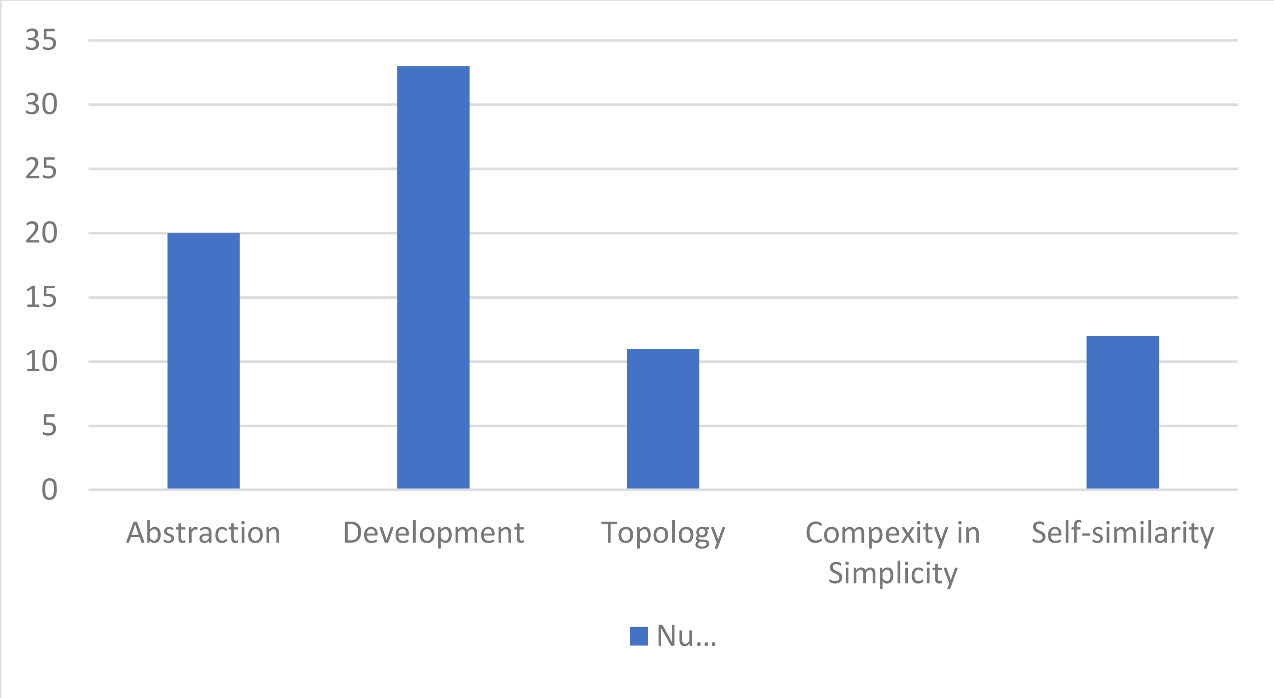


Fig. 18. Distribution of the concepts used in the scientific documentation on the L-systems application in architecture. Source: Authors.

complex topological concepts. For example, in plan design, the correct relationships between different spaces are very important, and should not be affected by changing the geometry. L-systems will have such a concept in their structure, which is applicable in design automation.

The concept of complexity in simplicity: Parametric designs with increasing data such as inputs and variables may become very complicated, which in addition to reducing the speed of processing, it will also be difficult to control them, and therefore some opportunities for the design options will be lost. Therefore the potential of L-systems in the compact description of the 3d object, reducing the volume of data and at the same time maintaining the complexity should be paid more attention to.

Concept of abstraction: "Symbols in L-systems can represent anything"; With such a metaphorical expression, it is possible to define different problems and provide various geometrical interpretations. Therefore, many possibilities are available to designers. For example, their symbols can include structural plan units, form units, repeating units in facades, etc.

Regarding the application of L-system in the evolution of form, the combination of L- systems with evolutionary algorithms is a very good idea, the methodology of which is correctly proposed, but it is still in its early stages and requires testing and checking the effect of applying operators in different parts of L-systems formalisms to generate structures according to fitness criteria. In applying these systems, it should be noted that almost all the applications have combined methodologies to improve the capabilities of L-systems, and pure L-systems are almost used only in generating simple branching forms. So, most of its applications were in the concept and early stages of design, and only a few cases were used in the modeling phase, and a few were used in detailed design. Therefore, the main potential of these systems is in the architectural concept stage, but they can also be used in detailed design. In addition, it can be seen that almost all examples of non-architectural applications are presented in authoritative sources, and growing research about L-systems in these fields is observed, which by observing new methodologies, architectural applications can also be developed.

Conclusion

After examining L-systems in the main context, this article divides and reviews its applications and potentials in architecture that have been published since 2000 in order to identify important approaches and trends. In this regard, by carefully studying the L- systems in the main sources, the main concepts of the L-system algorithm have been extracted, and their possible potential has been presented. Then, in a review study, the applications of L-systems in architecture and other fields were investigated and divided into seven sections which were briefly described. The purpose of such a comprehensive study was to observe the applications of these algorithms in other fields in order to inspire development in architecture. The reviewed documents were compared based on the type of reference, the scope of work, the main purpose, the application of the L-system, the methodology, the emphasized concepts of the L-system, and the design stage to use. The types of scientific documents are examined, and the importance of the subject is stated based on this. The specific research process, the reasons for their reduction, and suggestions for the development of these applications are stated. It can be seen that some applications in architecture have not been developed yet, which can be developed by reviewing the articles related to the L-systems. For example, no study was found on the use of "fast modeling with details" in architecture, but with inspiration from other methods used, it can be used in plan design or road networks or generating complex 3d objects. "Evolution of form" is still in the early stages of architecture, which can be used to create different geometric forms with specific design goals, and developing plugins and tools can be noted in this regard. The "patterns" generated with these systems, especially fractal patterns, are of interest in architecture, and they can bring more interesting results in combination with other algorithms. In the architecture of "branching structures" with L-systems, there are currently plugins that need to be developed for different purposes. The development of the application of "regulating the relationships of components" is also small in architecture, but the existing examples are very important. Optimizing structural topology, developing heating and cooling systems in different spaces, modeling plan connecting spaces, and, most importantly, adjusting plan relationships using this algorithm are the most important problems that can be considered in architecture. Modular structures and spatial distribution are also important in design, which requires the creation of new methods.

Finally, it seems that the use of L-systems is at the starting point of applied research in biomimetic architecture. These algorithms have not been sufficiently developed in architecture, and have not been addressed as much as they should be, and their potentials have not been used sufficiently. With a conceptual view of these systems and observing their methodologies and applications in other fields, it is possible to help develop their applications in architecture. Some areas that should be the subject of future comprehensive research are:

Combining different types of L-systems with genetic algorithms and analyzing the effect of applying genetic operators on different parts of the algorithm's structure;

Analysis of patterns of L-systems in architectural design and how to use them;

Analyzing environmental effects in creating forms based on L-systems in architecture

and investigating the dependencies of form parameters due to environmental forces;
Development of a new geometric interpretation for L-systems for use in architecture;
Comparison of growth patterns of L-systems of different plants in creating an architectural concept;
Development of an integrated conceptual methodology for simulating environmental impacts in architecture based on growth.

Reference List

• Alfaris, A. (2009). *Emergence Through Conflict The Multi-Disciplinary Design System (MDDS)*. (Unpublished P.hD thesis). Massachusetts Institute of Technology, Cambridge, USA.

• Alnobani, A. A. F. (2018). *Architectural Narratives Framework for Geometry Adaptation through Representations of Voxels and Tetra-Meshes*. (Unpuplished Master's Thesis). Carnegie Mellon University, Pittsburgh, USA.

• Antoniuk, I., Hoser, P., & Strzęciwilk, D. (2019). L-system Application to Procedural Generation of Room Shapes for 3D Dungeon Creation in Computer Games. *Advances in Intelligent Systems and Computing*, (889), 375–386.

• Arponen, E., Haggrén, E., Herneoja, A., Hinkka, E., Honkanen, H., Kanninen, M., Kosonen, S., Logrén, S., Lundén, E., Metso, O., Parkkali, M., Rautiainen, V., Tanska, T., Väisänen, A., & Österlund, T. (2009). *Generate - From algorithm to structure.* Oulun yliopisto: University of Oulu.

• Becker, S., Peter, M., Fritsch, D., Philipp, D., Baier, P., & Dibak, C. (2013). Combined Grammar for the Modeling of Building Interiors. ISPRS Annals of the Photogrammetry, *Remote Sensing and Spatial Information Sciences*, II-4/W1, 1–6.

• Bessa, M. (2009). Algorithmic design. *Architectural Design,* 79(1), 120–123.

• Byrne, J., Hemberg, E., Brabazon, A., & O'Neill, M. (2012). *A Local Search Interface for Interactive Evolutionary Architectural Design*. In: Proceedings of the International Conference on Evolutionary and Biologically Inspired Music and Art (Evo-MUSART'2012). pp. 23–34.Springer, Berlin, Heidelberg

• Byrne, J., Hemberg, E., & O'Neill, M. (2011). Interactive operators for evolutionary architectural design. *Proceedings of the 13th Annual Conference Companion on Genetic and Evolutionary Computation*, 43–44.

• Chu, K. S. (2014). *Karl Chu X Phylum project records.* Retrieved Jan 10, 2022, from https://www.cca.qc.ca/en/archives/440077/karl-chu-x-phylum-project-records.

• Coates, P., Broughton, T., & Jackson, H. (1999). *Exploring 3D design worlds using Lindenmeyer systems and Genetic Programming.* Evolutionary Design Using Computers. San Francisco, California.

• Coates, P. S., Appels, T., Simon, C. & Derix, C. (2001). *Current work at CECA Three projects : Dust, Plates & Blobs,* Proceedings of the 4th Generative Art Conference (GA).

• Coelho, A., Bessa M., Sousa A. A., F. Ferreira (2007). Expeditious modelling of virtual urban environments with geospatial L-systems. *Computer Graph Forum*, 26 (4), 769–782.

• Coelho, A., Sousa, A., & Ferreira, F. N. (2020). *Procedural modeling for cultural heritage.* Book Section.In Visual Computing for Cultural Heritage, edited by F. Liarokapis, A.Voulodimos, N. Doulamis, and A. Doulamis, pp. 63–81. Springer Series on Cultural Computing. Springer,

• Cham.Diniz, N. (2012). P*rocess-Driven concepts. 17th International Conference on Computer-Aided Architectural Design Research in Asia*. Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

• Dollens, D. (2005). *Digital Botanic Architecture. Art and Architecture in Digital Social-Contemporary City and Genetic City Conference*. Barcelona: Retrieved Jan 3, 2022, from: http://www.artyarqdigital.com/fileadmin/user_upload/PDF/Publicaciones_Jornada_ II/18-Jornadas_II._DennisDollens.pdf.

• Ei-Khaldi, M. (2007). *Mapping Boundaries of Generative Systems for Design Synthesis.* Massachusetts Institute of Technology, Cambridge, USA..

• Fernando, R., & Drogemuller, R. (2015). *Recapitulation in generating spatial layouts.* Proceedings of the 20th International Conference of the Association for Computer-Aided Architectural Design Research in Asia CAADRIA: Emerging Experiences in the Past, Present and Future of Digital Architecture, Daegu , Korea.

• Goos, G., & Hartmanis, J. (2004). *Applications of Evolutionalry Computing: Lecture notes in computer science. In Lecture Notes in Computer Science* (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) V. 106. Springer-Verlag.

• Gorgora.de. (2011). *Relational Growth Grammars, In Applications of Graph Transformations with Industrial Relevance" Springer-Verlag Berlin Heidelberg, Department Ecoinformatics, Biometrics and Forest Growth.* Göttingen: Georg-August University of Göttingen.

• Gu, N., Singh, V., & Merrick, K. (2010). *A framework to integrate generative design techniques for enhancing design automation.* New Frontiers: Proceedings of the 15th International Conference on Computer-Aided Architectural Design in Asia (CAADRIA). Hong Kong: Association of Computer-Aided Architectural Design Research in Aisa (CAADRIA), pp. 127–136.
• Hanafin, S., Datta, S., & Rolfe, B. (2011). *TREE FAÇADES Generative Modelling with an Axial Branch Rewriting System.* CAADRIA: Emerging Experiences in the Past, Present and Future of Digital Architecture, Daegu , Korea.
• Hartl, D. J., Reich, G. W., & Beran, P. S. (2016). *Additive Topological Optimization of Muscular-Skeletal Structures via Genetic L-System Programming.* 24th AIAA/AHS Adaptive Structures Conference, San Diego, California, USA.
• Hemberg, M. (2001). *GENR8 - A Design Tool for Surface Generation.* Massachusetts Institute of Technology, Cambridge, USA. Cambridge: MIT.
• Hemberg, M., O'Reilly, U.-M., Menges, A., Jonas, K., Goncalves, M. da C., & Fuchs, S. R. (2007). *Exploring generative growth and evolutionary computation in architectural design*. In: Machado, P., Morelo, J.J. (eds.) Art of Artificial Evolution, Springer,Heidelberg.
• Hemberg, M., & O'Reilly, U. M. (2004). Extending Grammatical Evolution to Evolve Digital Surfaces with Genr8. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, (3003), 299–308.
• Hensel, M. (2006). Computing Self-Organisation: Environmentally Sensitive Growth Modelling. *Architectural Design*, 76(2), 12–17.
• Hensel, M., & Menges, A. (2006). Material and digital design synthesis. *Architectural Design,* 76(2), 88–95.
• Hornby, G. S., & Pollack, J. B. (2001). The advantages of generative grammatical encodings for physical design. Proceedings of the IEEE Conference on Evolutionary Computation, *ICEC*, (1), 600–607.
• Hornby, G. S. (2004). Functional scalability through generative representations: The evolution of table designs. *Environment and Planning B: Planning and Design*, 31(4), 569–587.
• Ikonen, T. J., Marck, G., Sóbester, A., & Keane, A. J. (2018). Topology optimization of conductive heat transfer problems using parametric L-systems. *Structural and Multidisciplinary Optimization*, 58(5), 1899–1916.
• Jackson, H. (2002). Toward a Symbiotic Coevolutionary Approach to Architecture. In D. W. C. Peter J. Bentley (Eds.), *Creative evolutionary systems.* Burlington: Morgan Kaufmann.
• Jones, M. (2012). Retrieved 3 Jan, 2022, from https://meganjonesdesign.wordpress.com/
• Jormedal, M. (2013). *Procedural generation of road networks using L-systems [Linköpings universitet].* Retrieved 3 Jan, 2022, from http://www.vehicular.isy.liu.se/Publications/MSc/09_EX_4227_JL.pdf
• Kahn, S. (2008). *Thinking Outside The Grid: Structural Design Through Multi-parametric Growth and Self-Adaptive Analysis.* Cincinnati: University of Cincinnat.
• Kearney, A. C. (2015). *Multi-objective optimization of aerostructures inspired by nature.* Hawai: university of Hawai.
• Khetan, A., Lohan, D. J., & Allison, J. T. (2015). Managing variable-dimension structural optimization problems using generative algorithms. *Structural and Multidisciplinary Optimization,* 52(4), 695–715.
• Kiptiah Binti Ariffin, M., Hadi, S., & Phon-Amnuaisuk, S. (2017). *Evolving 3D models using interactive genetic algorithms and L-systems.* In Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)", 10607 LNAI(i), 485–493.
• Kniemeyer, O., Barczik, G., Hemmerling, R., & Kurth, W. (2008). *Relational Growth Grammars – A Parallel Graph Transformation Approach with Applications in Biology and Architecture.* In Sch¨urr, A., Nagl, M., and Z¨undorf, A., editors, Applications of Graph Transformations with Industrial Relevance, volume 5088 of Lecture Notes in Computer Science, pages 152–167. Springer Berlin Heidelberg.
• Kobayashi, M. H. (2010). On a biologically inspired topology optimization method. *Communications in Nonlinear Science and Numerical Simulation*, 15(3), 787–802.
• Landreneau, E., Ozener, O. O., Pak, B., Akleman, E., & Keyser, J. (2006). Interactive Rule-Based Design. Book Section, In J. P. van Leeuwen & H. J. P. Timmermans (eds.), *Innovations in Design & Decision Support Systems in Architecture and Urban Planning*. Springer, Printed in the Netherlands.
• Lane, B. (2015). *Cell complexes: The structure of space and the mathematics of modularity.* Alberta: University of Calgary.
• Lorenzo-Eiroa, P. (2013). *Architecture in Formation*. London & New York: Routledge.
• Marinčić, N. (2019). An overview architecture and computation. In N. Marinčić (Ed.), *Computational Models in Architecture.* Birkhäuse: De Gruyter.

• Marvie, J. E., Perret, J., & Bouatouch, K. (2005). The FL-system: A functional L-system for procedural geometric modeling. *Visual Computer*, 21(5), 329–339.

• McDermott, J., Swafford, J. M., Hemberg, M., Byrne, J., Hemberg, E., Fenton, M., McNally, C., Shotton, E., & O'Neill, M. (2012). String-rewriting grammars for evolutionary architectural design. *Environment and Planning B: Planning and Design*, 39(4), 713–731.

• McQuillan, I., Bernard, J., & Prusinkiewicz, P. (2018). Algorithms for inferring context-sensitive L-systems. Book Section, *In "Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*", 117–130.

• Menges, A. (2006). Polymorphism. *Architectural Design*, (76), 78–87.

• Menges, A. (2009). *New Czech National Library in Prague.* Retrieved Jan 3, 2022, from http://www.achimmenges.net/?p=4452.

• Mikkelsen, M. K. (2020). *Applications of parameterized l-systems for preliminary structural design and optimization. (*Unpublished P.hD Thesis). A&M University, Texas, USA.

• Mishra, J., & Mishra, S. (2007). *L-systems Fractals.* In Elsevier, Radarweg 29, PO Box 211, 1000 AE Amsterdam. The Netherlands.

• Mountstephens, J., & Teo, J. (2020). Progress and challenges in generative product design: A review of systems. *Computers*, 9(4), 1–23.

• Narahara, T. (2010). *Self-organizing Computation A Framework for Generative Approaches to Architectural Design.* Massachusetts: Harvard University.

• Nordin, A., Hopf, A., & Motte, D. (2013). *Generative design systems for the industrial design of functional mass producible natural-mathematical forms.* Retrieved Jan 3, 2022, from http://lup.lub.lu.se/record/4113641/file/4113677.pdf

• O'Neill, M. & Brabazon, A. (2008). *Evolving a logo design using Lindenmayer systems, Postscript & Grammatical Evolution.* 2008 IEEE Congress on Evolutionary Computation, CEC.

• O'Reilly, U. M., & Hemberg, M. (2007). Integrating generative growth and evolutionary computation for form exploration. *Genetic Programming and Evolvable Machines,* 8(2), 163–186.

• Österlund, T. (2013). Design possibilities of emergent algorithms for adaptive lighting system. *Nordic Journal of Architectural Research,* (1), 159–184.

• Pan, Y. C. (2007). *Inverted Skyscraper Typology.* Retrieved Jan 2, 2022 from https://www.evolo.us/inverted-skyscraper-typology/

• Parish, Y. I. H., & Müller, P. (2001). Procedural modeling of cities. Proceedings of the 28th Annual Conference on Computer Graphics and Interactive Techniques - *SIGGRAPH '01*, (6), 301–308.

• Peter, M. (2017). Modelling of indoor environments using lindenmayer systems. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, *XLII-2/W7(2W7)*, 385–390.

• Popovici, E. (2005). Evolving Families of Designs Using L-Systems. *Department of Computer Science George Mason University Technical Report Series* (Issue GMU-CS-TR-2005-8).

• Prusinkiewicz, P., Cieslak, M., Ferraro, P., & Hanan, J. (2018). Modeling Plant Development with L-Systems. In R. J. Morris (Ed.), *Mathematical Modelling in Plant Biology*. Switzerland: Springer..

• Risi, S., & Togelius, J. (2020). Increasing generality in machine learning through procedural content generation. *Nature Machine Intelligence*, 2(8), 428–436.

• Romero, J. J., & Machado, P. (2008). The Art of Artificial Evolution. In J. Romero & P. Machado (Eds.), *Springer-Verlag Berlin Heidelberg.* Berlin: Springer.

• Runions, A., & Prusinkiewicz, P. (2012). Computational models of plant development and form. *New Phytologist,* 193(3), 549–569.

• Ryan, C., O'Neill, M., & Collins, J. J. (2018). *Handbook of grammatical evolution.* Berlin: Springer.

• Saleri, R. (2020). *The Fatal Birth of Architecture: The Obligation of Order.* Retrieved Jan 3, 2022, from http://www.springer.com/series/15179

• Sharp, A., Blay, G., Kholodova, J., & Correa, D. (2021). *An Autonomous Bio-Inspired Shading Façade System based on Plant Movement Principles*. Towards a New, Configurable Architecture - Proceedings of the 39th ECAADe Novi Sad. Serbia.

• Shiffman, D. (2012). *The Nature of Code.* Retrieved Jan 3, 2022, from https://onlinelibrary.wiley.com/doi/abs/10.1002/9781119546665.ch2

• Soltanzadeh, A. & Masnavi, M. R. (2017). *Inspiration from dendriform structures for the design of the column and roof to cover large openings using the Linden Meyer system*. 4th National Conference on Applied Research in Civil Engineering, Tehran, Iran.

• Tang, P. (2005). *Co-generative 3D Form : The Framework of Co-generative Design System.* Proceedings of the 10th International Conference on Computer Aided Architectural Design Research in Asia, New Delhi, India

- Taylor-Hell, J. (2005). *Incorporating biomechanics into architectural tree models.* Processing of 18th Brazilian Symposium of Computer Graphic and Image, Natal, RN, Brazil.
- Wonka, P., Aliaga, D., Müller, P., & Vanegas, C. (2011). *Modeling 3D urban spaces using procedural and simulation-based techniques.* SIGGRAPH '11: ACM SIGGRAPH 2011 Courses, SIGGRAPH'11.
- *Ydroponic-garden* (2009). Retrieved Jan 3, 2022, from https://www.worldarchitecturenews.com/article/1500277/hydroponic-garden
- Петрушевски, Љ., Деветаковић, М., Митровић, Б., & Дабић, М. (2010). *Development and Application of Explorative Tools in the Field of Architectural.* Geometry: L-Systems.

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