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Original Research Article

The Application of Evolutionary Algorithms and Shape Grammar in the Design Process Based upon Traditional Structures*

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Abstract

Problem statement: Although the application of shape-based methods in the generative design systems has been studied as a means for describing or analyzing a style, regional architecture, or a specific design in numerous works of literature, the complexity and multiplicity of the structural grammars, as well as the lack of flexibility in the system for evaluation and optimization of new models has somewhat dwindled the applicability of these approaches. However, in addition to investigating and extracting the shape grammar of a traditional structure, the potential of generating novel designs based upon the shape rules indicates the necessity of further examination of the shape-based approaches.

Research objectives: Addressing the issue, this study proposes a hybrid generative evolutionary approach. The use of generative evolutionary methods can provide fresh insight into the process of analyzing traditional structures and designing new ones based on these structures.

Research method: The methodology is based upon library studies with the analytical-descriptive approach to examine the related literature review. Furthermore, with the consideration of Kashan's traditional houses as a case study, it applies the combination of shape grammar method for analyzing configuration characteristics and physical-spatial relationships in historic houses, with genetic algorithm for optimizing the new generated forms.

Conclusion: The results of the study indicate the effectiveness of generative evolutionary methods in improving and accelerating the process of analyzing the characteristics of traditional structures as well as producing a variety of new designs that can preserve the spatial essence of traditional structures.

Keywords: *Generative Evolutionary Design, Evolutionary Algorithms, Shape Grammar, Rule Schemas, Genetic Algorithm.*

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Introduction

In the conventional design process of a new structure based on the traditional ones, attaining an optimum answer, including a range of design from literal replication to intentional opposition, has always been the concern of architects. In most cases, designers apply the conventional method of design involving their priorities and personal preferences, which has not necessarily been a proper response to the environment. The "Generative Evolutionary approach" with novel techniques and methods, has started to simplify the descriptive-analytic process of studying traditional structures and achieving an optimized solution.

Although the issue of generating has been intrinsic through the conventional design process, the application of tools that are a part of a designer's mind and hand and resulted in various optimal solutions (algorithms) has emerged in the early twentieth century. Since then, a new stage of design tools has been under development. These tools are described active against passive as they are not only an integral part of the manual design process but they are also a part of the cognitive design process. Also, in addition to analyzing and evaluating, such applications can explore and generate novel design alternatives. These tools aim to free the designer from design determination and limitations of conventional reasoning, thus enabling the exploration process among various possible solutions to a design problem.

The novel process investigated and analyzed in this study is the combination of evolutionary and generative methods to improve and accelerate the design process. For this purpose, in the first part, research area description, two general categories of evolutionary and generative methods have been examined and in the second part, the application of Shape Grammar (generative) and Genetic Algorithm (GA) is described. Also, in the third chapter, to investigate the generative evolutionary process as a responsive one for analyzing traditional structures and developing new patterns, the number of 30 case studies among 50 historical houses from the Qajar dynasty in Kashan, Iran, have been selected. Since each design process pursues specific goals based on design problem or context, it is possible to evaluate new samples by appointing the proper fitness function and adopt the fittest solution among multiple explored generations.

Research questions

In this study the main question is as follows: how to achieve an interactive system for generating new architecture samples based on grammar rules of traditional architecture by combining evolutionary and generative method?

Literature review

To analyze the research case studies, Kashan traditional houses, Shape Grammar has been applied as a generative approach. This method was first introduced by Stiny and Gips (1971) in article entitled "Shape Grammars and the Generative Specification of Painting and Sculpture". Since then, this method has been applied for analyzing a specific architecture style such as Giuseppe Terragni, Frank Lloyd Wright, Glenn Murcutt and Christopher Wren architectural Style as well as traditional Japanese tea houses, Queen Anne houses and historic houses of Turkey, Taiwan and the plethora of otherstyles (Stiny & Mitchell, 1978; Koning, 1981; Flemming, 1987; Knight, 1991; Duarte, 2005). With examining literature review regarding the analysis of traditional structures with shape grammar between 2014 to 2018 among ISI journals, the studied aspects of this method, including two and three-dimensional forms, parametric, descriptive-analytic and geometric methods, as well as various methods of deriving spatial characteristics of traditional structures were studied and analyzed. The basic methods, common ways of generating forms based on rules, in shape grammar are appropriate for analyzing a traditional structure, but not suitable for interacting between several complex structures. For example, Lee, Ostwald & Gu (2015) in their article "A syntactical and grammatical approach to architectural configuration, analysis and generation" combined Space Syntax and Shape Grammar approaches to analyze "Glenn Murcutt"[1]'s houses. Ligler and Economou (2015) in their article "Lost in translation: towards an automated description of John Portman's domestic architecture" investigate shape grammar through John C. Portman's houses, an American neo-futuristic architect and present the challenges and opportunities of this translation in the larger context of shape computation (ibid.). Most articles in the field of shape grammar have analyzed either an architectural style, or have studied methods of optimizing the generated samples separately. However, few studies have comprehensively examined the application of shape grammar in the conceptual design process. This research seeks to propose a hybrid design system based on traditional structures by combining shape grammar to extract physical-spatial features and an evolutionary algorithm (genetic algorithm) to optimize new generations.

John Frazer was one of the first people to use evolutionary methods in design, especially in architecture and structural design and to study the generative aspect of evolutionary algorithms (Frazer, 1995). Also, Karl Sims (1994) reviewed early experiments of applying GA in graphic and virtual creatures design. Various studies and projects have been carried out in relation to form finding for architectural and structural design with evolutionary processes (Kicinger, 2005; Janssen, 2005). As an instance, Berk Ekici et al. in their study entitled "Addressing the high-rise form finding problem by evolutionary computation" (Ekici, Kutucu, Sarıyıldız & Taşgetiren, 2015), used two evolutionary algorithm, "NSGA-II" and "DE", in early design process of high rises which would focus on computational performance and architectural features of the resulting alternatives. In addition, some studies have been conducted on the combination of optimizing the architectural form and design efficiency from a structural perspective by synthesizing the generative method and genetic algorithm (Von Buelow, 2010). In studies examining objective functions related to architectural problems, combination of various evolutionary methods has been followed. In generative design systems using target functions for the optimization process, stochastic optimization algorithms such as genetic algorithms (GA) can be applied in the exploration and generation process. However, most studies in this context have dealt with optimization problems with performance-oriented approaches and the use of hybrid methods in the early conceptual design stage has been less studied. The examples of studies applying hybrid methods can been found in the field of brand and product design (Mckay & Pennington, 2006) and jewelry design (Kielarova & Pradujphongphet, 2015). As an instance of the combination of shape grammar and GA in architectural studies, "A general indirect representation for optimization of generative design systems by genetic algorithms" can be mentioned (Granadeiro, 2013). In this article shape grammar has been used to parametrize Frank Lloyd Wright's prairie houses' design rules and with GA design solutions, the alternatives were optimized through one objective function. This article mainly focuses on genetic algorithm representation in a design programming system and does not refer to the generative evolutionary design as a system for designing based on traditional structures. Fig. 1 is an illustration of generating the floor plan based on set rules in MATLAB software.

Research methodology

This paper applies a descriptive-analytic method with library studies to first categorize and analyze literature review in generative, evolutionary and hybrid methods. Then, through field survey and the analysis of 50 case studies among Kashan traditional houses in the Qajar dynasty, 30 houses have been selected and with the application of shape grammar compositional rules are presented. The rules are translated in MATLAB software as equations and variables to generate the first generation coherent to compositional rules. Then, the objective functions are defined according to the compositional rules and optimized with genetic algorithm. The research structure includes three section: 1- Description of research field and analysis of generative evolutionary theories, 2- Study and analysis of the application of these theories to analyze traditional structures and generate new designs and 3- Application of shape grammar method and genetic algorithm in achieving the spatial compositional rules of traditional

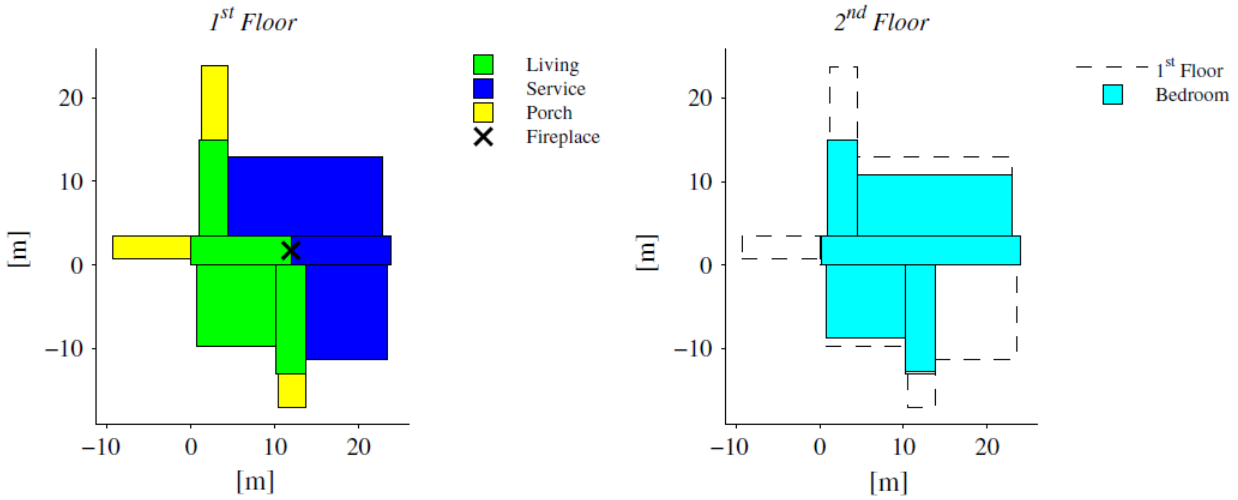


Fig. 1. Two plan examples generated via set rules in MATLAB. Source: Granadeiro, 2013.

structures in case study (traditional houses of Kashan) and optimizing selected generation by genetic algorithm. Fig. 2 depicts the structure of this research.

Evolutionary computing process (EC)

The evolutionary computational process is a field of research in computer science that is inspired by the mechanisms of natural evolution. EC has been used successfully in a variety of fields, such as in the fields of art, biology, chemistry, economics, engineering, genetics, physics, robotics and so on. Although architecture designed based on this approach can be called organic, it does not necessarily mimic the forms of natural organisms; instead, it uses natural processes and structures simulated from biology. In general, there has been a shift in opinions towards the natural design process and "nature" as a source of forms has altered to "nature" as a range of intertwined and dynamically related processes that can be simulated and applied in the design process and the creation of architecture (Hensel, 2010). EC, as a Meta heuristic, together with genetic algorithm, Neural network, Ant system, Particle Swarm Optimization (PSO), Artificial Bee Colony Algorithm (ABC) and so on, forms the foundation of the evolutionary science. Evolutionary computation methods typically include evolutionary algorithms (EA), evolutionary strategies (ES), genetic algorithms (GA) and genetic programming (GP), all of which simulate the process of natural evolution. Although there are differences in the mechanism of mutation and crossover between these methods, they all involve evolutionary solutions (evolved population) based

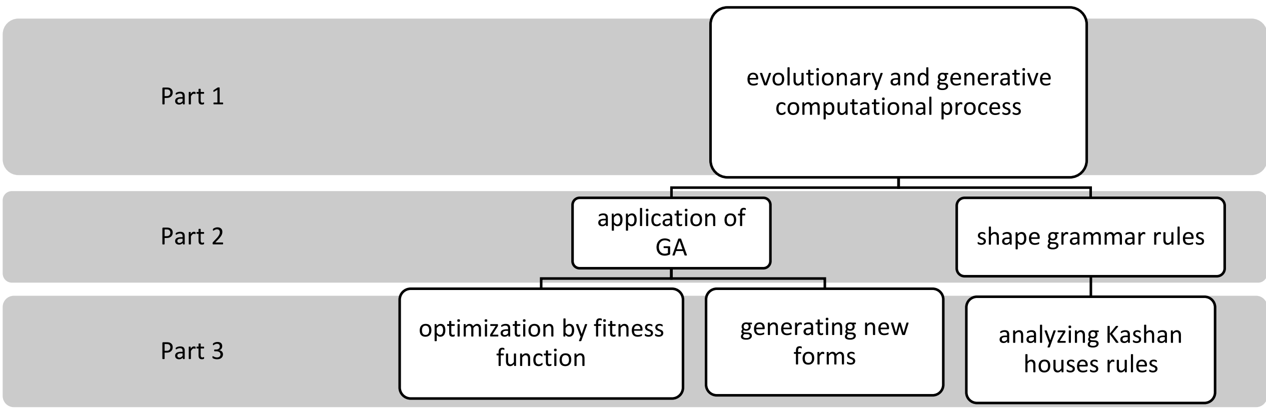


Fig. 2. Research structure. Source: authors.

on optimal selection in the environment (objective function). The term evolutionary algorithms express a set of statistical optimization methods that are based on the simulation of the natural evolution process. In the 1970s, several evolutionary algorithms were introduced, including Genetic Algorithm (GA), Evolutionary Programming (EP), Evolutionary Strategies (ES) and so on. Many architectural problems have two types of problems, one is the existence of several conflicting goals and the other is the existence of a very complex and extensive search space. In such problems, instead of finding an optimal solution, a set of adaptive solutions is obtained, which is called Pareto optimal solutions (Caldas, 2002). If the goals do not take precedence over each other, neither of these answers is superior to the other. This feature is very important in the design process based on new structures; Because the extensive and seemingly contradictory parameters involved in this design process have challenged the use of linear design methods.

The application of GA

Genetic Algorithm, although is proposed after the Evolutionary Strategy (SE) algorithm, it is the most popular method among evolutionary algorithms. In a genetic algorithm, a population of individuals survives in the environment according to their appropriateness. Individuals with higher potentials have a better chance of crossover; thus, after some generations, a fitter population will form. In the genetic algorithm, each person in the population is introduced as a chromosome. Chromosomes have become more complete over several generations. In each generation, the chromosomes are evaluated and, in proportion to their value, are able to survive and multiply. Generations in GA are created with mutation and crossover operators. The fittest parent is selected based on the fitness function. GA structure can be described as follows:

1- Chromosome: a bit string which represents a possible encoded solution, either fit or unfit, of a designated problem. The basis of the genetic algorithm is to convert each set of answers into a coding. This coding is called a chromosome (Sadeghi Moghadam, 2009);

2- Fitness function: It is a function in which the problem variable is placed, thus determining the desirability of each answer (ibid.). In optimization problems, the objective function is used as a fitness function. In other words, $F(n)=g(f(x))$ in which f is the objective function and the function g converts the value of the objective function to a non-negative number and F is the corresponding fit value. The appropriateness or inadequacy of the answer is measured by the value obtained from the fitness function. Because the problem is of optimization type, the fitness function is the same as the objective function. The objective function considers the problem of cost minimization;

3- Population size and production number: The number of chromosomes is called population size. Population size has been studied in various experiments and the population is improved from one generation to another in order to find a better answer using crossover methods (ibid.).

Regarding the characteristics of genetic algorithm, in comparison with other optimization methods, it can be said that it is an algorithm that can be applied to any problem without any knowledge of the problem, without any restriction on the type of its variables and its efficiency has been proven in finding Global Optimum. The efficiency of this method is to solve complex optimization problems that conventional methods are either not applicable or the global optimum is not reliable (Bäck, 2000). Fig. 3 shows the typical operation of a genetic algorithm, in which the population of K evolved from generation n to n+1 through the process of selection, crossover and mutation.

Generative design

Generative design can be defined as the process in which multiple potential solutions are identified by algorithms. As “Lars Hesselgren”[2], director of KPF Research explains, “Generative design is not about designing a building”, “It’s about designing the system that designs a building”. Stiny and Mitchell (1978) implicitly define generative systems by having multiple

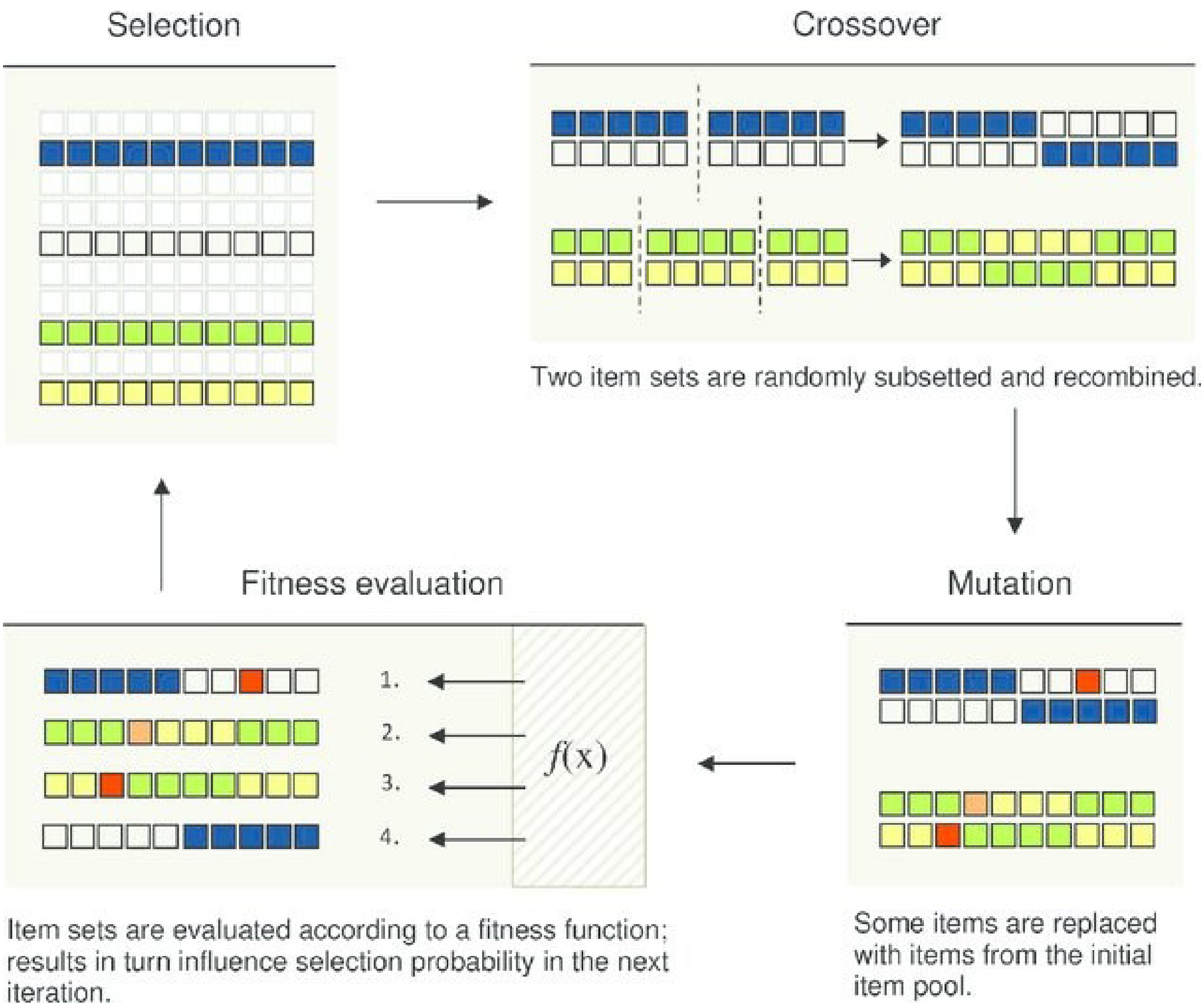


Fig. 3. Generic genetic algorithm function illustration. Source: Schroeders Wilhelm & Olaru, 2016.

architectural elements that belong to specific vocabulary and are arranged in different combinations to produce an architectural form. Generative architecture is defined more generally by the use of a generative system, such as a set of language rules, a computer program, a set of geometric transformations, a diagram, or other procedural innovations in the design process by which the final design is produced. The generating system has different degrees of automation from fully automated process to step by step user-controlled process. This process includes designing the algorithm (rules), setting the initial shapes and parameters, advancing the adaptation process and finally selecting the best option. The maturity of generative systems in architecture occurred after the development of architecturally-based software in the mid-twentieth century. One of the first systems written in architecture based on shape grammar (shape rules) was to generate Villa Paladin. Stiny and Mitchell (1978) created parametric shape grammar which not only generated Villa Paladin's ground plans, but it also created novel ground plans coherent to their initial pattern. Their first attempt was to redesign parts of Palladio's architectural rules in a modern way and generate a form (ibid.). At the same time, William Mitchell published "The Logic of Architecture: Design, Computation and Cognition" (Mitchell, 1990) in which he describes design process concepts such as algorithms, evolution, rules and logics. Despite the tremendous potential of generative systems for the generation of forms that would be considerably difficult without digital technology, the main advantage of these systems is the continuous exploration of projects and the generation of multiple alternatives rapidly and tirelessly.

The application of shape grammar

The design process in shape grammar can be divided into three stages: “Idea generation phase, Level one, the Conceptual phase, the development or “adjustment” phase and the detailed phase” (AbdulRaheem, 2016). For generating the scheme, first the methods of shape grammar by which the forms can be combined, should be identified (the idea stage). Such specific compositional methods can be defined by spatial relations. The form A and B combined by spatial relations are denoted by A+B and can generate four shape rules. Two of these rules are related to addition and the other two are about subtraction.

(1) A→A+B (2) B→A+B (3) A+B→A (4) A+B→B

Once the compositional idea or spatial relation is identified, a set of simple rules called basic rules are defined (adjustment phase). The initial form for designing will be included in each rule. When generating initial schemes which are derived from spatial relations, a more complex shape rules can be developed (the detailed phase). Such complex rules generate intricate schemes which are created from the combination of basic rules. Complex rules are defined either from developing initial rules or combining them. For example, one simple way to extend the rules is to combine two or more set rules with the same spatial relationship into a single rule. Complex rules can be achieved not only by extending the rules but also by complicating the basic forms. The shape grammar method can also be divided according to the defined constraints in this method. One of the constraints is based on the type of rule that relates to the forms and labels that may be seen in the rule. Another type of constraint relates to the way of applying the rule, which refers to the state in which the rules are repeated consecutively and is related to the number of repetitions of the rule. Knight (1999) believes that such constraints increase the generative potential of shape grammar. Based on the two mentioned constraints, he proposes six models of rules: basic grammars, nondeterministic (ND) basic grammars, sequential grammars, additive grammars, deterministic grammars and unrestricted grammars. In deterministic grammars only one output is possible and the applied rules generate one or no scheme of the previous sample. In contrast to this model, the indeterministic method leads to various designs. Applying the rules, in search of new designs and options of a particular style, by deriving common features of a particular type of buildings that can be analyzed in a category, has the ability to produce new designs of that particular style. Accordingly, a set of rules derived from the analysis of buildings relating to a particular style and with common features should be specified. Fig. 4 illustrates the general structure of shape grammar process.

Case study analysis

In order to examine the hybrid generative evolutionary method, case studies were selected among traditional houses (as a function model) in the hot arid climate (as the dominant climate of Iran) and in Kashan city. Out of 50 houses surveyed, 30 houses were selected and typologically analyzed. Table 1 classifies traditional houses based on the spatial relations between mass and space, including single-yard categories with two construction fronts facing each other, two adjacent construction fronts, three construction fronts, four construction fronts, two courtyards and several courtyards.

Furthermore, the samples are analyzed based on six sub-criteria of 1. orientation of structural elements (courtyard, porch [ivan or eyvān], main room, side room and entrance), 2- dimensions and size, 3- geometry, 4- spatial organization, 5- percentage of solid and void and 6. symmetry for each house as well as in comparison with each other. From the analysis of the results obtained from the six sub-criteria, the geometric parameters of the initial shapes, spatial relations between solid and void and the compositional layout of elements are obtained, which is used in shape grammar. The description of the shape grammar process for single-courtyard houses is as follows:

1- Determining the initial shapes: in the first stage,

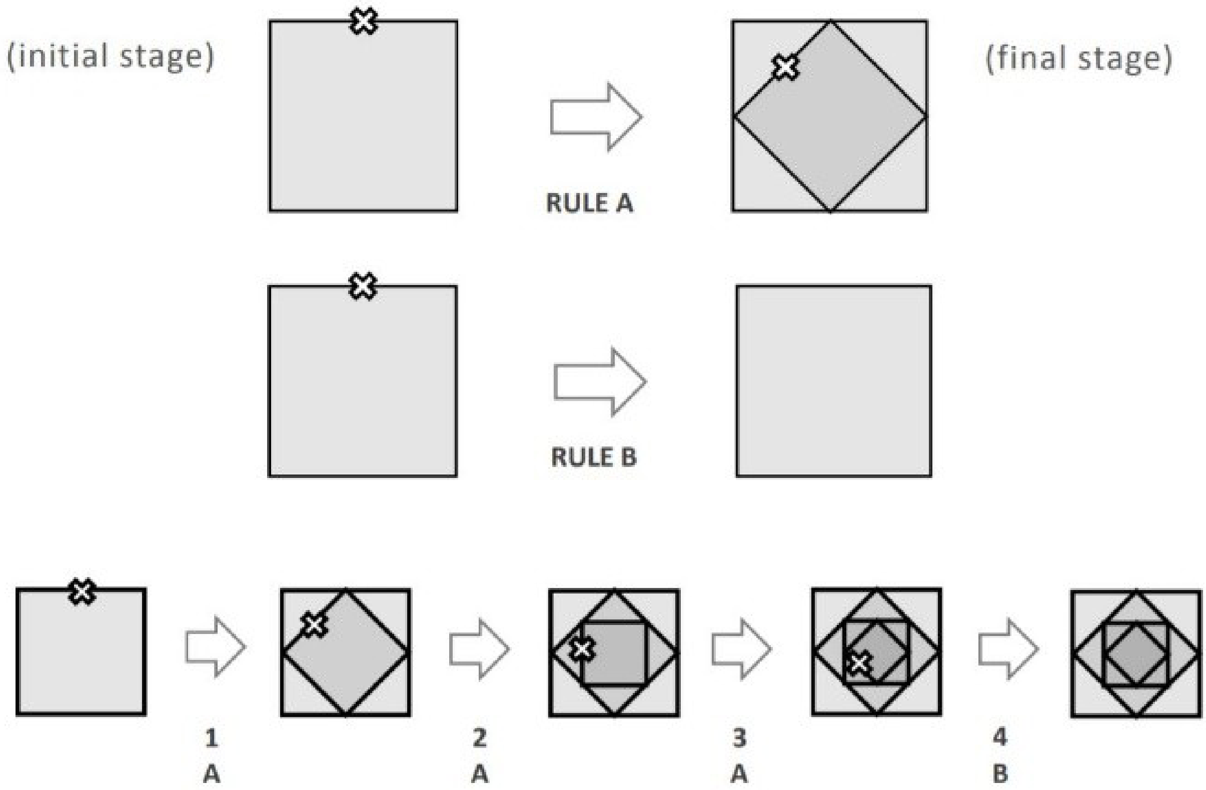
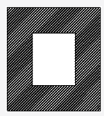
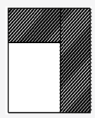
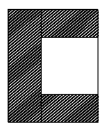
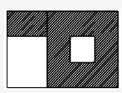
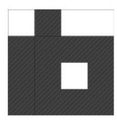


Fig. 4. Grammatical shape rules, Rule A is repeated three times and rule B once. Source: Benrós, 2018.

Table 1. Classification of case studies based on solid and void. Source: authors.

House type		Building name					Diagram
Single-courtyard houses	Four construction fronts	Rahmati	Sajjadi	Saheb	Farshad	Lazizi	
	Two facing fronts	Abrishami	Azadmanesh	Saleh	Azizzadegan	Philsouf	
	Two adjacent fronts	Balalzade	Pahlavanzade	Hajqorban	Karkhanechi	Golizade	
	Three construction fronts	Esfehanian	Aleyasin	Banikazemi	Tahami	Sharifian	
Two and three courtyard houses	One “biruni” exterior and one “andaruni” interiors courtyard	Ostovar	Bafande	Bakhshi	Taj	Sadoori	
		Barforoush		Mohtashami			
	One “biruni”[3] exterior and two “andaruni” interiors courtyards	Borujerdi-ha	Tabatabaei		Alageband		

based on Downing and Flemming (1981) ideas all shape grammars related to the architectural plans' generation have a geometric pattern that determines the compositional features of the plans. To obtain a set of parametric shapes, five main elements have been selected, including the courtyard, the porch, the main room, the side room and the entrance. Fig. 5 depicts these shapes with respect to quantitative geometric parameters, as well as the dependent relationships between the parameters.

Fig. 6 shows the possible types of location and coordinates of the yard in relation to the surrounding mass space based on the geographical direction and location of the mass construction in single-yard houses. The seven modes shown in this diagram are based on the analysis of case studies from single-yard houses and they are the main structure for the production of new samples.

2- spatial relations and its rules: Fig. 7 shows the classification of spatial relations between the six elements of the courtyard, the second courtyard, the porch (ivan), the main room, the side room and the entrance. The first category of RG1 is related to the spatial relations between the courtyard and the porch, which itself consists of 9 separate rules. The second category RG2 illustrates the combination of the main room and the porch and includes 5 rules. The third category RG3 shows the combination of the main room and the side room and has 6 rules. The fourth category of RG4 depicts the spatial relations between the side-rooms with each other and includes 6 rules. The fifth category of RG5 or 6 rules shows the relationship between courtyards and the RG6 rule shows the types of relations between the entrance and the yard with 9 rules. RG7 is the seventh rule category with 10 rules showing the relationship between the main room and the yard. These rules are derived from the compositional analysis of case study.

Fig. 8 illustrates the possible types of spatial relationships between the courtyard, as an open space, porch, as a semi-open space and the closed space according to the geographical direction and according to all four types of single yard with two facing fronts

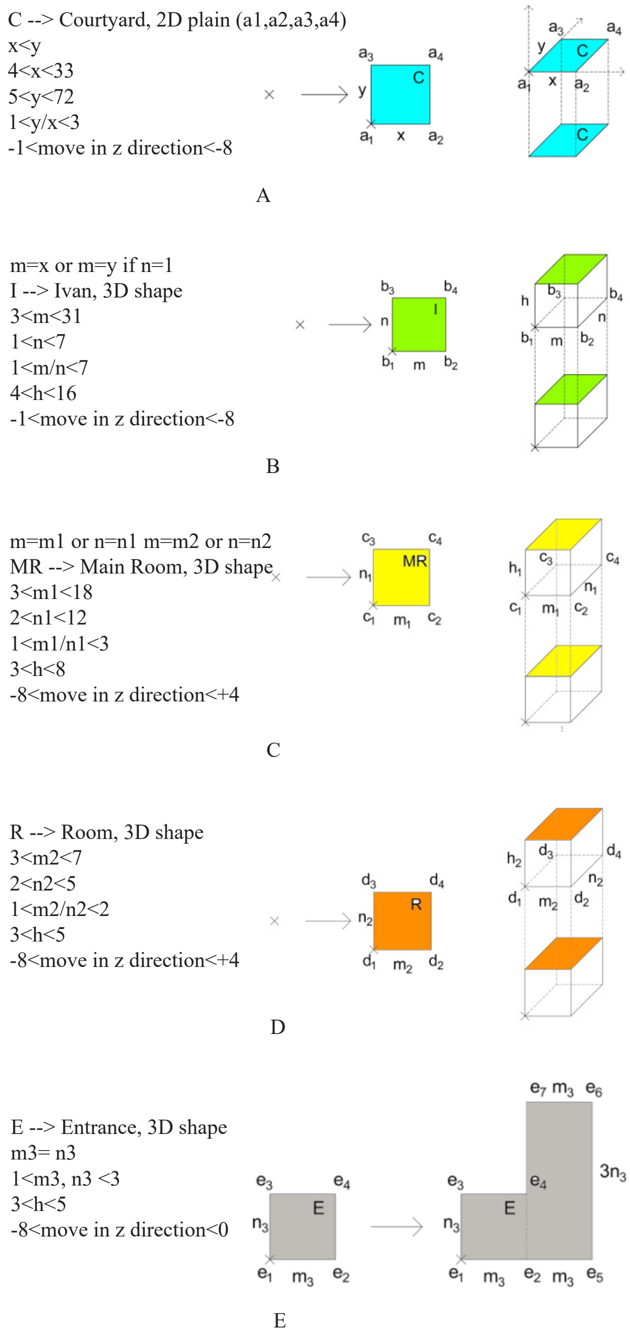
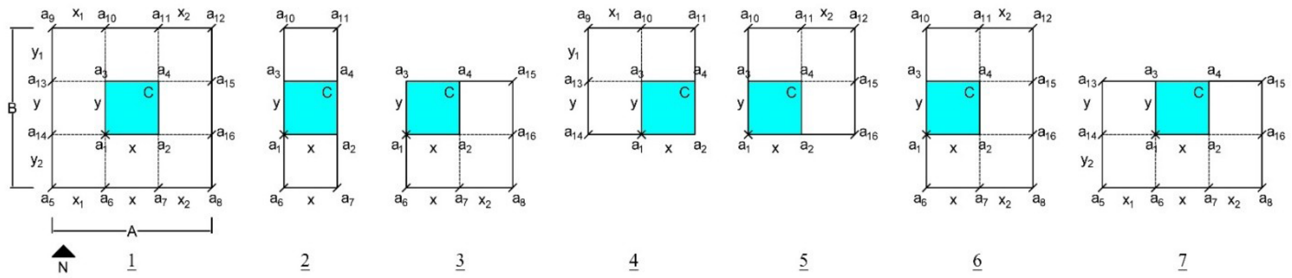


Fig. 5. Parametric presentation of initial shapes including A) Courtyard, B) Porch (ivan), C) Main Room, D) Side Room, E) Entrance. Source: authors.

(A), two adjacent fronts (B), three fronts (C) and four fronts (D). As can be seen in this diagram, the porches are similar in proportion to that of three-door rooms (se-dari), or with a shallow depth (1 to 1.5 meters) the same length as the rooms, or extended along one of the courtyard sides. Also, the number of smaller porches on one side can vary between one and two porches.



A= x1+x+x2
B= y1+y+y2
14<A<55

13<B<101
A<B
1<A/B<2

5<x1<10   5<x2<12
4<y1<17   4<y2<12

Fig. 6. Position and parametrization of courtyard based on surrounding mass and geographical direction derived from case study analysis. Source: authors.

The location of the porches is based on maintaining symmetry between sides of the courtyard and where different porches have been built on the fronts, the symmetry has been maintained by columns on the facade. In Fig. 8, the northern front is considered upwards and the porches are drawn accordingly.

3- Identifying the constraints and geometric preferences: The geometric and coordinate (spatial) constraints of the samples, which were extracted based on typological analysis with six sub-criteria, lead to the following statements when comparing the samples with each other:

- The symmetry axis passes through the middle of a central courtyard's side or one of its diameters;
- The allowed number of porches is between one to five;
- If there are two porches on one axis (side of the yard), they are equally spaced from the center of the courtyard, or in other words, they are symmetrical;
- The axis of the central courtyard coincides with the axis of the adjacent space on each of the sides. This means that the center of one of the spaces located next to the yard must be the same as the center of that side of the yard;
- Porches that are facing each other and are based on an axis of symmetry are the same size;
- If the length of the porch is equal to the length of each side of the yard, the depth of the porch is one meter;

Also, by analyzing the physical-spatial aspects of the case samples based on the orientation, geometry, proportions and the ratio of solid and void, we achieve the desired proportions, which are as follows:

- The entrance is located in eight geographical directions and the number varies between one and four entrances;
- The ratio of length to total width of the building is from 1 time (relatively equal length and width) to 2.8 times (almost three times) and the average of this ratio is 1.5 times approximately (1:√2);
- The ratio of length to width of the yard varies from equal to 3.1 times and the average of this ratio is 1.4 (1:√2);
- In two-courtyard houses, the area of the private inner yard (andaruni) is more than the area of the public outer courtyard (biruni), which has a ratio of 3 to 12 times;
- The geometry of the main rooms (five-doors (panj-dari) and the hall (talaar or shahneshin) in the summer or winter accommodation (seasonal rooms) varies from approximate square (length 1.1 times the width of the room) to rectangular with a ratio of length 3 times as width. The average length to width ratio of the main rooms is 1.8 times (almost double).
- In the form of a lower courtyard (Godal Baghcheh) (with Sharemi or lower semi-open space) with a level of up to 8 meters in the basement or in the form of a yard slightly below the entrance level (average level is one meter lower than the ground level). Therefore, the two-dimensional plate of the central courtyard has the ability to move between levels -1 to -8.
- The average height of the basement is 4 meters, the average height of the main room is 6 meters and the porch is 8 meters;

Fig. 7. Classification of spatial relation rules based on case study analysis. Source: authors.

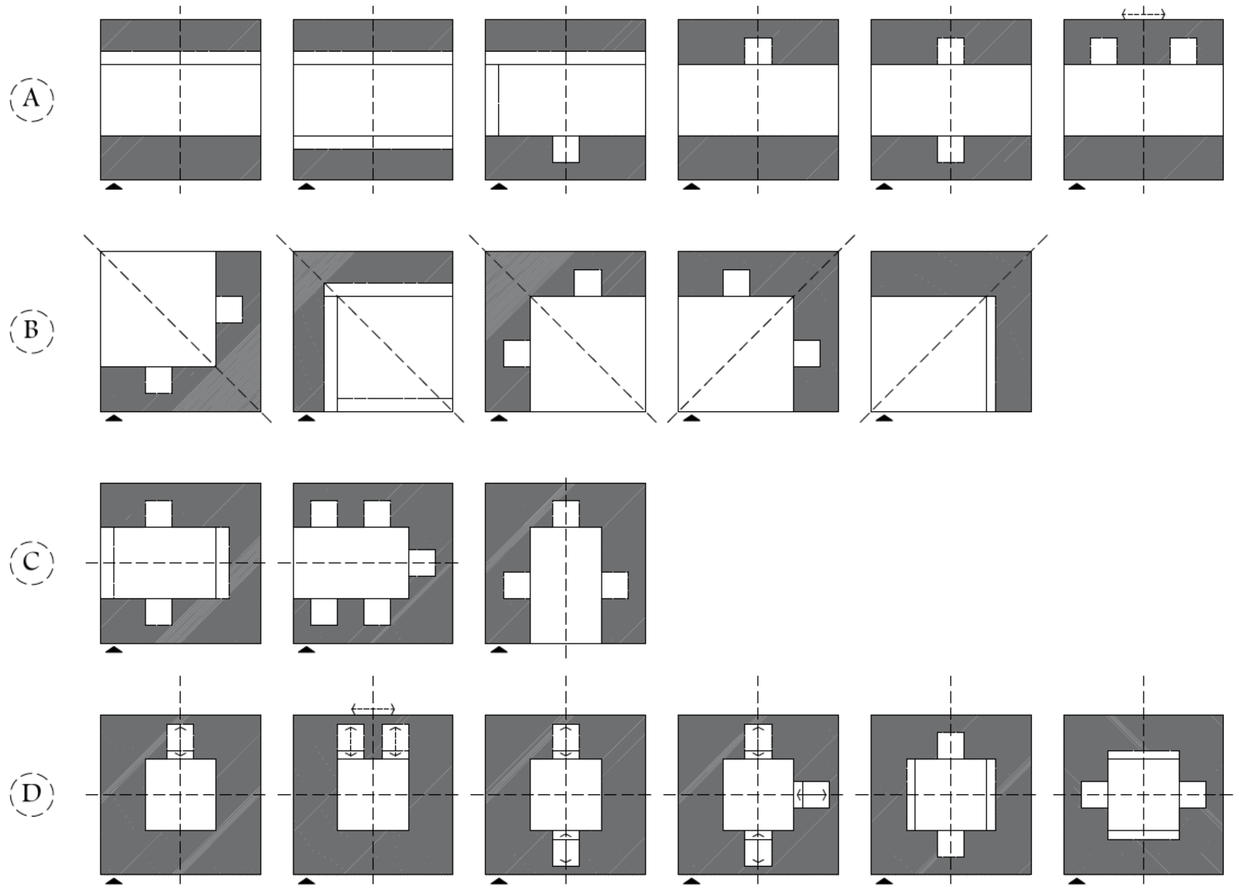


Fig. 8. Spatial relationships between the main elements including solid, courtyard and porch (Ivan) based on geographical direction derived from case study analysis. Source: authors.

- The depth of the porches is less in the case samples and the ratio of length to width in the stretched porches (connecting several rooms to the yard) is up to 1:17. The proportion of the main porches, which are located in the center and axis of the courtyard, is 1.4 (1:√2);
- The highest percentage of mass is in the northern and southern sides with an average of 34 and 30%, with the exception of four-front houses in which the highest percentage of mass is located in the southern side (summer accommodation) with an average of 37 percent mass and then the mass is distributed in the northern, Eastern and Western sides;
- The average ratio of closed to open space is 1.7 times (almost double) and the average ratio of semi-open space to closed is 0.2 times.

Form finding with parametric design system

The parametric design system includes a geometric model that encodes the shape properties according to its solution space. Shape features are the same spatial and topological relationships between the various elements of the samples (the main elements including the yard, room, porch) and their size variables. These relations are defined as a set of functions with variables that can use different numbers based on a specified range. The spatial relationships between the elements of case studies are numerical and complex and include multiple and dependent functions and variables. These relations, unlike shape grammar, contain symbolic information such as numbers and can therefore be used in a wide range of programs in parametric programming.

The application of algorithmic design in the conceptualization and conceptual design stage requires programming and scripting[4] knowledge by the designer, as it needs to be pertinent to the designer's ideas and problems. In another method, which includes the use of plugins (default ready algorithms in software), the designer can use ready-made components without the need for programming knowledge, which of course requires editing and, in some cases, redesigning the plugins. Several programming languages such as JAVA Script, Python and MATLAB have been used for coding. In this study, MATLAB software, due to its many advantages over other languages[5], was used to generate examples in the conceptual stage.

In this step, first the obtained parameters from the initial shapes and the spatial relations between the elements are coded in MATLAB software. In this way, a set of configurational rules and deterministic constraints is coded and the initial population of possible states of spatial relationship and geometric-spatial constraints of the elements is generated. Fig. 9

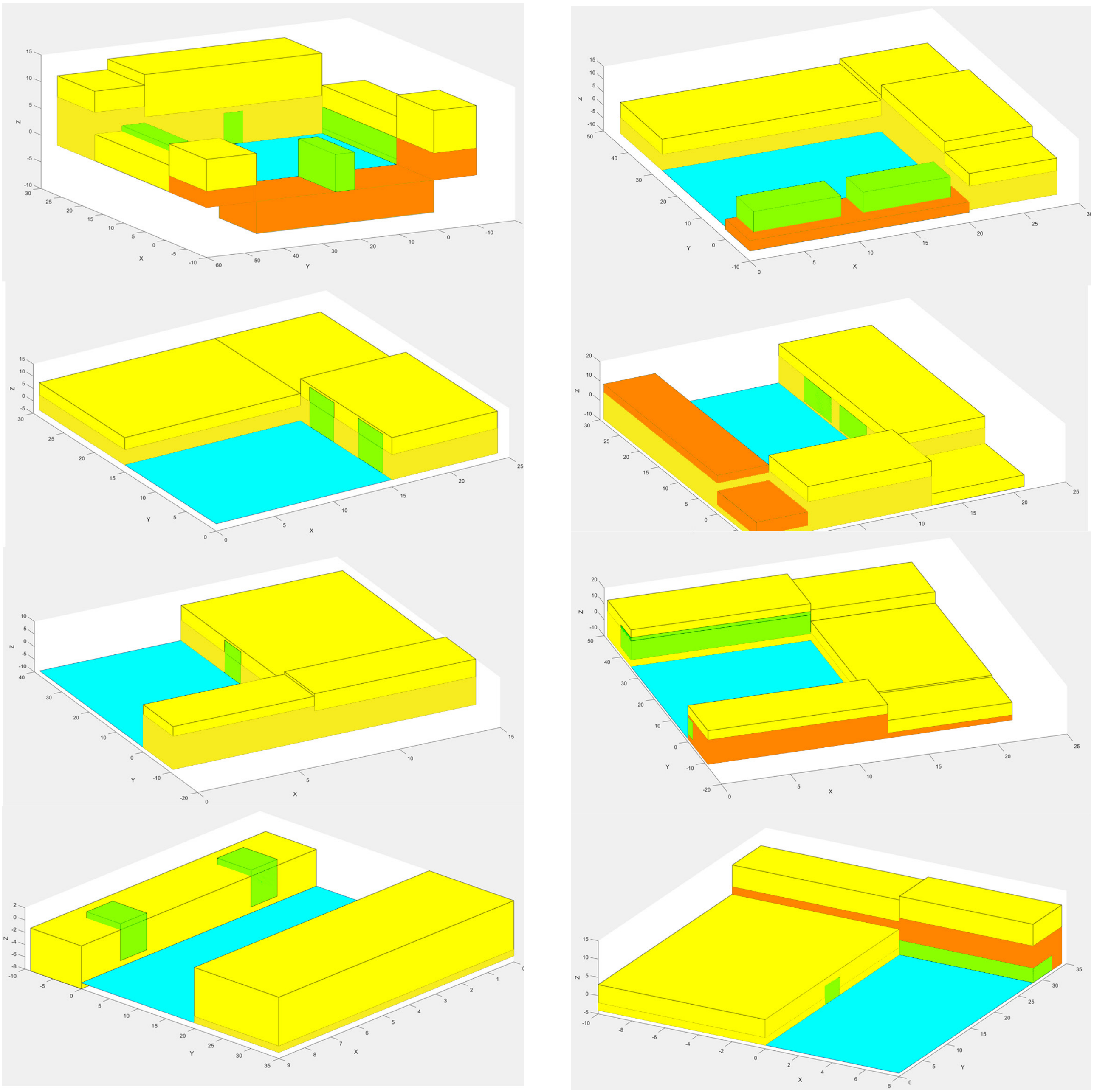


Fig. 9. Randomly generated alternatives from the initial population in MATLAB. Source: authors.

illustrates the obtained results from the generated samples in the first step. These Figs. show the generated plans from the stochastic selection of the variables in the designer programming system.
As can be seen in the Figs., in each randomly generated population, one of the seven cases presented in Fig. 6 is created according to the rules of courtyard and mass and the porches and rooms are created according to the relevant rules and diverse parameters.

Form optimization

The obtained parameters from analyzing case studies are dynamic parameters including a range of numbers, which leads to the generation of countless samples. Also, some of these parameters are dependent and their values are dependent on other elements (such as the values of the porch and the yard, which are interdependent due to symmetry rule). From this wide range and countless examples produced, those options are considered desirable that can be a suitable answer to the objective function. The objective functions of this research are defined based on the optimal geometric structure and location of the elements. Therefore, for each of the elements of the courtyard, the main room, the side rooms and the porch, the length, width, height and position of movement in the desired Z axis (LZ location) (closest to the proportions of traditional structures) are defined. Van Buelow (2009) proposes "three different approaches to the use of GAs in selecting values for parametric variables to explore a design space: Subjective – selection (based on form alone), Combined (selection based on form+performance), Objective (selection based on performance alone)". "The subjective approach represents a scenario where no objective criteria are used to determine the fitness function of the GA". However, similar to natural process, new generation occurs based on selection possibility. The optimization process in this study is "combined" and based on form and performance. The degree of importance of efficiency or the importance of form is determined by the weight selected for each fitness function by the designer. The advantage of this approach is that the designer can, while aesthetically examining the form, select the desired performance options and advance the new generation based on this choice.

Proportion fitness functions

- Minimum courtyard area in which the ratio of length Y to width X is the closest to $\frac{Y}{X} = \frac{1+\sqrt{5}}{2}$ or the golden ratio. This function can be written as:

$$(1)\ \min x_c y_c + \left(\frac{yc}{xc} - \frac{1+\sqrt{5}}{2}\right)^2$$

in which x is the width and y is the length.
- Minimum courtyard area $x_C y_C$ in which the ratio of closed space to the courtyard is 1.7 and the ratio of porch area to closed area is 0.2 and that of the porch to the courtyard is 0.3.

$$(2)\ \min x_c y_c + \left(\frac{x_M y_M}{x_c y_c} - 1.7\right)^2 + \left(\frac{x_I y_I}{x_m y_m} - 0.2\right)^2 + \left(\frac{x_I y_I}{x_c y_c} - 0.3\right)^2$$

The defined ratios in Function (2) are obtained from the proportion analysis and the geometry criteria in case studies. In the same way, the considered functions can be obtained and finally these functions are combined to solve multi-objective optimization. Fig. 10 shows the optimal possible state after adding the two fitting functions. The optimization process of this example can be seen in Fig. 11.
The optimization process starts with the population of 100, obtaining the optimum solution in 60 generations. This value starts at 700 at the beginning

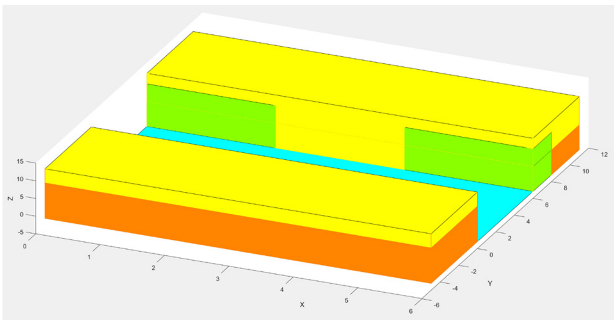


Fig. 10. Optimum solution among all the states after optimization by the fitness function. Source: authors.

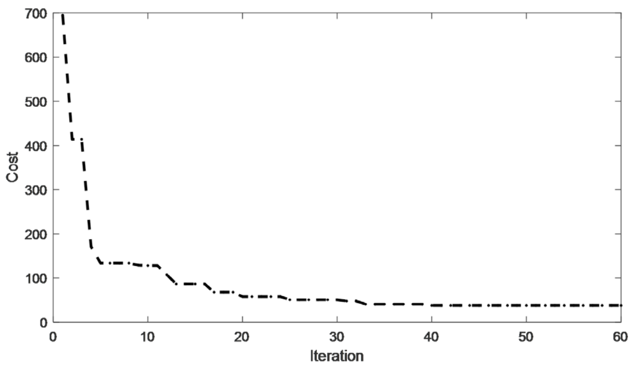


Fig. 11. Case study optimization process through 60 generations in MATLAB. Source: authors.

of the process and the optimum value is 37.8. The crossover rate is considered 0.6 and the mutation rate is 0.001. Table 2 gives information about the values of the optimal solution variables. In the first stage, fitness functions are considered for all generated solutions. Achieving the above example is done with an automated process, but it is also possible to select the desired alternative from the seven modes based on the needs and limitations of the design space and then consider the optimization process for that particular mode. In this case, the process is under the supervision and control of the designer and is semi-automatic. The designer can store any of the countless initial solutions and use them for future changes. Fig. 12 shows the most optimal options created for each of the seven mass and courtyard modes (except for the second mode, which was selected as the most optimal mode in Fig. 10).

Fig. 13 illustrates the implementation process of the genetic algorithm in the MATLAB program. The number of repetitions in each step can increase depending on the answers obtained. At each stage, after applying the desired functions, exploration of the optimal solution begins. This step can be done under the supervision of the user, the designer and the best answers can be saved. The stored solutions are collected in the pool for the crossover stage. The next generation of generated solutions is reassembled and mutations are performed on the second generation. If the optimal answers are satisfactory from the user's point of view, the optimization process is over and if the answers are not suitable, the generation will be re-evaluated.

Conclusion

Design theories and strategies pursue the objective of exploring novel solutions and creative designs. For designers, the process of achieving the right design can be far more fundamental than finding the right answer. In designing new structures based on the traditional ones, complex, intertwined and sometimes contradictory layers as well as extensive parameters are involved. Analyzing the involved parameters by conventional and linear design systems is not only time-consuming, but it also cannot provide the designer with extensive exploration space. In this study, a generative evolutionary system was proposed to address this challenge. In the research process of this study, an attempt has been made to eliminate the shortcomings of the analyzed literature, which include the following:

- Considering the implementation method more than the generative evolutionary potentials;
- Focusing on solution representation in the design programming system;
- Focusing more on performance-oriented aspects;

Table 2. Values of the optimal solution variables. Source: authores.

One of the seven modes of relation between the courtyard and mass	State number 2- two facing fronts
Porch (ivan) rule	Two symmetrical porch on one side
Number of the mode	1
Courtyard coordinate	X=(0,6), y=(0,6), z=(-3)
Main rooms coordinate	(0 6) (6 11) (4 12) (0 6) (-5 0) (7 11)

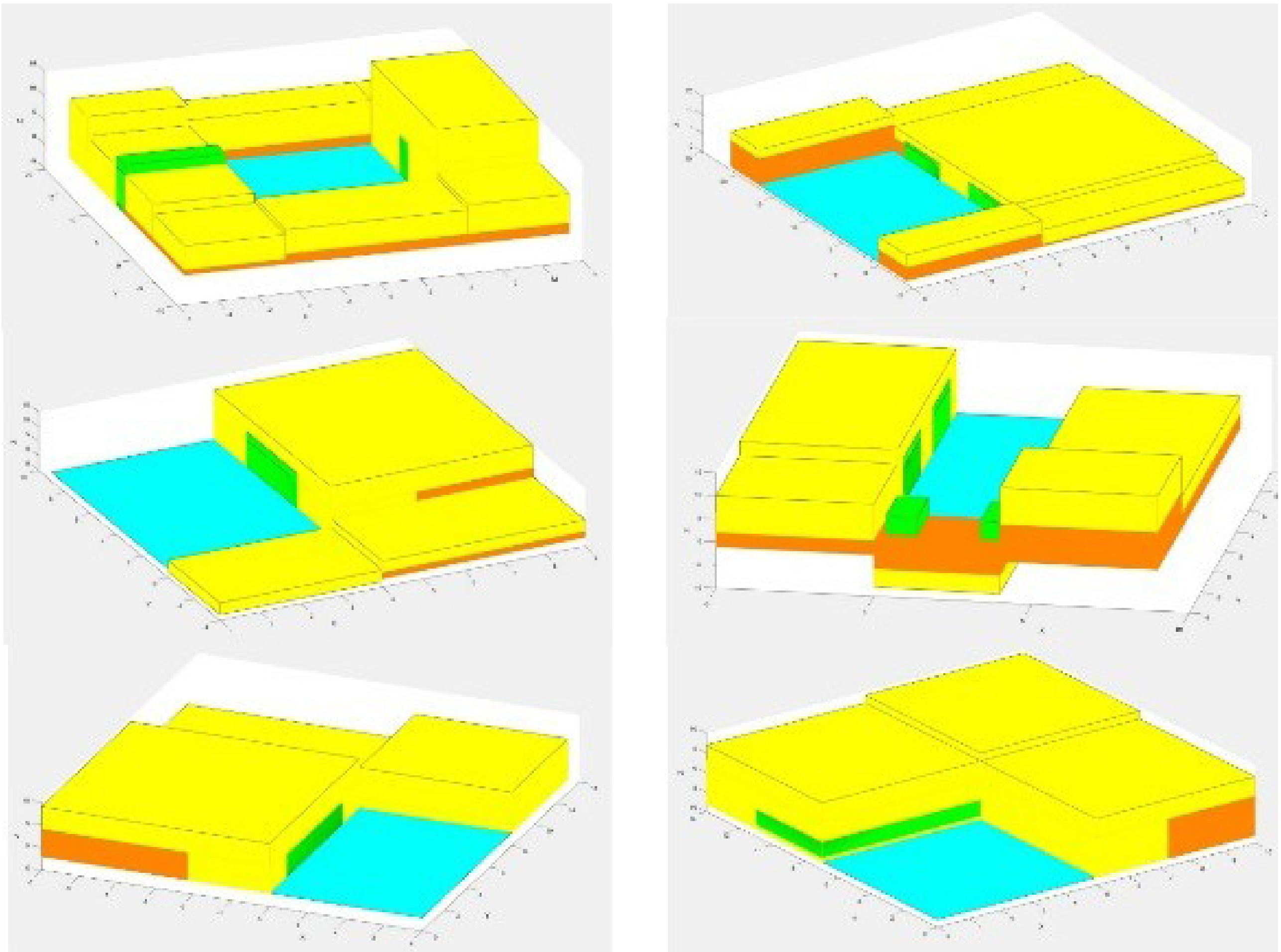


Fig. 12. Optimum solutions in the 60th generation for 1,2 and 6 mode of mass and courtyard. Source: authors.

- More consideration on the exact simulation of traditional structure;
- Less intervention of extensive dependent variables;
- Lack of qualitative analysis of fitness functions based on the design problem.

This research proposes a generative evolutionary system that represents a cyclic and hybrid process of using shape grammar for form finding and genetic algorithm for optimization, in the conceptual phase of design. This process considers the combination of form and performance and has the flexibility to be controlled by a designer. In fact, the designer can re-script new functions at each design stage based on the emerging needs or constraints, or can restore desired alternatives and optimize them. Therefore, the designer can interact with solution exploration process to select the new generation based on aesthetic issues. The main outcome of the study can be seen in Fig. 14. Furthermore, the typology method has been used to analyze the physical-spatial features of the case studies both qualitatively and quantitively. In addition, six sub-criteria have been presented to evaluate individual potentials of cases separately, as well as in relations with each other. This research provides a proper foundation for the future studies in various fields of performance-oriented form finding systems in the conceptual design phase based on the traditional structures.

Endnote

1. Glenn Murcutt is an Australian architect and winner of the Pritzker Prize.
2. Hesselgren is director of research at Kohn Pedersen Fox Associates (KPF), an international design studio and a cofounder of the Smart Geometry Group, a nonprofit collective that is taking the lead in bringing generative design concepts to real-world architectural projects, mainly through a series of groundbreaking conferences.

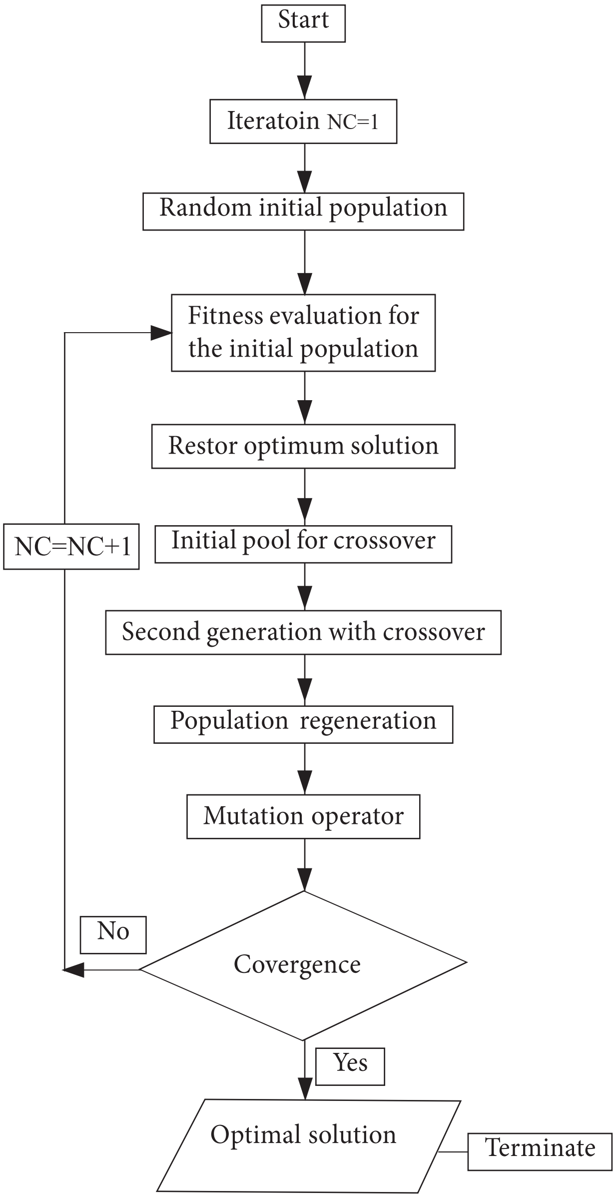


Fig. 13. Optimization implementation with genetic algorithm. Source: authors.

3. In Iran's traditional residential architecture, "Biruni", or exterior, is a public courtyard, dedicated to guests and strangers and it is usually in a square or a rectangular form. Whereas "Andaruni", or interior, is a private courtyard for the family where women can interact with the family members without following their dress code. These courtyards play an organizing entity role in the house structure, around which the other functional areas are formed.
4. In computer programming terms, a script is a program that will run with no interaction from the user. The use of this knowledge in computer-aided design or CAD programs has become common today and based on it, several plug-ins have been added to CAD programs such as Rhino and Revit.
5. There are many characteristics or functions available in the MATLAB environment which makes it better than many other programming languages. Some of the characteristics of MATLAB are different predefined functions, integration support with other environments and visualization tools for custom plots and graphics.

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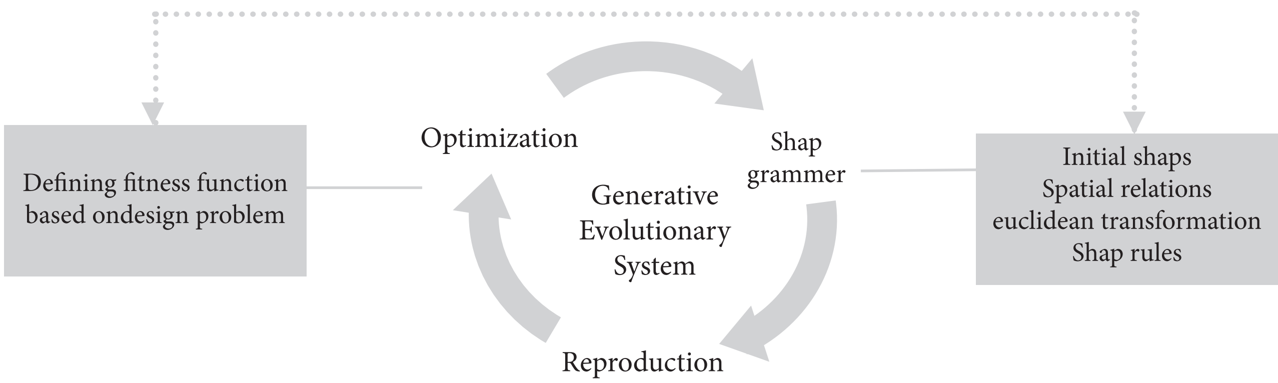

Fig. 14. The proposed Generative evolutionary system model. Source: authors.

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