

Prioritizing store plan alternatives produced with shape grammar using multi-criteria decision-making techniques

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Abstract

To generate alternatives and variations of specific architectural models, shape grammars can be used by applying a set of geometric rules step by step. With the development in human life, advances in store design, design concept, commercial buildings' architectural and spatial fiction, the magazine of the interior, and facade design cause rising competition between stores and also between designers. For this reason, in this paper we study the evaluation of store plan alternatives produced with shape grammar using two of multi-criteria decision-making (MCDM) techniques with fuzzy numbers, namely fuzzy analytic hierarchy process and fuzzy analytic network process. The main contribution of this paper is to prioritize plan alternatives using numerical methods with experts' view. To the authors' knowledge, this will be the first interdisciplinary study which uses MCDM techniques for evaluating shape grammar outputs in architectural design.

Keywords

Computer aided design, shape grammars, store design, decision making

Introduction and literature review

People since ages in order to meet different requirements of various spaces have embarked on a search due to their own quest for space accommodates. In shaping the nature of space in a variety of human needs and requests plays an important role. This configuration gives the determinants of physical, cultural phenomena or may be living habits.

Design is a purposeful knowledge-based human activity whose aim is to create form which, when realized, satisfies the given intended purposes (Rosenman and Gero, 1994).

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Design is a fundamental, purposeful, pervasive and ubiquitous activity and can be defined as the process of creating new structures characterized by new parameters, aimed at satisfying predefined technical requirements. It consists of several phases, which differ in details such as the depth of design, kind of input data, design strategy, procedures, methodology, and results (Renner and Ekrárt, 2003). Computers have been used extensively for all these stages of design except the creative conceptual design phase. Our world is becoming increasingly infiltrated and mediated by electronic systems and devices. The role of design is shifting in response to these changes (McCormack et al., 2004).

The conventional design methods affect in the same way computer-aided design factors of design and this will impact on the design process, computer-aided design tools, and designers' communication. The designer has the chance to check the options as which rule applies where, when, how, and when to start, when it will end. In this way, decisions are provided by the designer, so the method of design control and the flow is directed. If the designer can predict which can reproduce the forms and software in this direction control, the nature of work and wealth can be increased as well.

In the world of design with the use of the computer as a common, computer logic can be easily adapted to the computer environment that is compatible with the rule-based design methods. Several methods for computer-aided architectural design were presented in the literature, such as shape grammar (Duarte, 2001), genetic algorithms (Chu, 2004), swarm intelligence (Hoar et al., 2002), L-system (Lindenmayer, 1968), cellular automata (Wolfram, 2002), etc. In this paper, outputs of shape grammar, one of the computer-aided architectural design methods, are studied.

During the second half of the 20th century, a number of architects recognized computation as a powerful tool for solving certain architectural problems. In the 60s Allen Bernholtz and Edward Bierstone utilized computational algorithms in order to decompose complex design problems into simple sub-problems and then to recompose a solution (Rocker, 2006). At the same time, computational algorithms were used in calculation of tensile structures for the first time. One of the first attempts of using computational approach in art and architecture started with work of George Stiny and James Gips. In their seminal article published in 1971, they found Shape grammar, first design-oriented generative system (Stiny and Gips, 1972).

Shape grammar is a system of rules for the design language to define and create spatial compositions. Rule-based design methods are made with the format, which is one of the grammar logic of a design method to analyze; even subtracting the format rules, the rule change, which is sited to the base of the design of the computer environment with the logic of the same design or convert it to possible new designs creation.

In grammar-based design method, the relationship between forms and design builder is the basic idea. These relationships not only can be constructed based on the geometry of pure form, but also the form can be edited according to the meaning given to. Form selection and determination of the relationship between forms are determined by design problems, program, and designer's review.

In shape grammars rules are not expressed as a symbolic expression, are directly expressed through with shapes. Shape rules can be considered as steady answers given to steady states. However, the rules of grammar do not limit creativity, the tools are only used in creating a way from known to unknown. Authors used shape grammars for various areas in the literature, such as Turkish House design (Çağdaş, 1996a), vase motifs of Greeks (Knight, 1986), garden design of Mughul (Stiny and Mitchell, 1980), etc. In this study, outputs of shape grammar for store design are presented and prioritized.

Places are shaped in accordance with the principles set according to the needs of people. This is for a variety of actions depending on the requirements to places that needed different functions.

In the first ages, trade concept, which means exchange of goods, had always been a part of human life. Afterwards trade concept had changed in parallel to the development in human life. In parallel with economic and technological developments, hand trucks or outdoor area open markets had been moved indoors with the change of community life and commercial buildings' architectural and spatial fiction.

Shopping takes its importance from not only being a necessary relief, but also being a social action in human history. Stores generally offers similar product types, that customer walk around, analyze, try, and buy products inside. In recent years, stores are classified according to the species of selling goods and to their position. In designing a shopping venue, the magazine of the interior and facade design have important roles. Firstly, in store's interior design, sold product and the nature of the product are determined. Then according to the product, the design concept of the store is emerged. Depending on their potential customer and the store design, the rules are created. In this paper, creating a set of plan alternatives and choosing the best alternative that are difficult for designers, store owners, and architects, are handled.

Selecting or prioritizing alternatives from a set of available alternatives with respect to multiple criteria is often referred to multi-criteria decision-making (MCDM). MCDM is a well-known branch of a general class of operation research models which deal with decision problems in the presence of a number of decision criteria. This class is further divided into multi-objective decision-making (MODM) and multi-attribute decision-making (MADM). There are several methods in each of the above categories. Priority-based, outranking, distance-based, and mixed methods are also applied to various problems. Each method has its own characteristics and such methods can also be classified as deterministic, stochastic, and fuzzy methods (Pohekar and Ramachandran, 2004).

In this paper we applied two MCDM methods to select the best store design alternative produced with shape grammar, namely fuzzy Analytic Hierarchy Process (AHP) and fuzzy analytic network process (FANP). This is the first paper in the literature to apply these two techniques for the selection of store design alternatives.

AHP is one of the common methods with which MCDM problems can be solved. The first application to solve MCDM problem in the literature was Saaty's choosing a school for his son using AHP (Saaty, 1980).

The AHP is an approach that is suitable for dealing with complex systems related to make a choice among several alternatives by providing a comparison of the considered criteria and alternatives. AHP is based on the subdivision of the problem in a hierarchical form. By reducing complex decisions to a series of simple comparisons and rankings, then synthesizing the results, AHP not only helps the analysts to arrive at the best decision, but also provides a clear rationale for the choices made. The objective of using AHP is to identify the preferred alternative and also to determine a ranking of the alternatives when all the decision criteria are considered simultaneously (Mahmoodzadeh et al., 2007).

ANP is also another common method with which MCDM problems can be solved. The decision problem is structured hierarchically at different levels in the methodology (Mikhailov, 2003). The local priorities in ANP are established by means of pairwise comparisons and judgments (Promentilla et al., 2008). The analytical network process is a generalization of Saaty's Analytical Hierarchy Process, which is one of the most widely employed decision support tools (Promentilla et al., 2006). The priorities in the ANP are

assessed indirectly by means of pairwise comparison judgments (Mikhailov and Singh, 2003).

ANP is a useful tool for prediction and for representing a variety of competitors, their assumed interactions, and their relative strengths to wield influence in making a decision (Tuzkaya et al., 2010).

The rest of this paper is organized as follows: a brief description about shape grammar is given in “Shape grammar” section, the problem definition is described in “Problem definition” section. Fuzzy AHP methodology and fuzzy ANP methodology are presented in “Fuzzy AHP methodology” section and “Fuzzy ANP methodology” section, respectively. In “Application: Evaluation of plan alternatives” section, we show an application of fuzzy AHP methodology and fuzzy ANP methodology in evaluation of plan alternatives. Computational results are given in this section. Finally, comparison of the results and future research directions are discussed in “Conclusion” section, which concludes the paper.

Shape grammar

In recent years, most of architects use computers as an efficient representation tool for modeling and drafting architectural forms. One of the first applications of digital technologies in architectural practice was related to writing scripts, which is a set of instructions assembled in order to solve complex design problems providing help with the decision-making process (Tepavčević and Stojaković, 2012).

Shape grammars generate languages of architectural design. Rule-based formalisms that encode syntactical knowledge of architectural designs have been studied in many researches about shape grammars (Çağdaş, 1996b).

Shape grammars are graphical production systems that provide a formal mechanism for generating compositions based on shapes and their spatial relationships by specifying methods to replace parts of shapes with others (Liew, 2004). They have been used for the last 40 years since the first publications in 1972 by Stiny and Gips.

A shape is composed of a finite collection of labeled or unlabeled points, lines, planes, areas, or solids. A rule in shape grammars can be written in the form $A \rightarrow B$ where A and B are shapes. When this rule $A \rightarrow B$ is applied, an instance of shape A is replaced with shape B . There are also parametric shape grammars which mean the shapes have parameters that can be adjusted (Stiny, 1980). Figure 1 exemplifies a shape grammar based on a vocabulary and one simple addition rule. Despite the simplicity of this grammar described by Knight (1999) it can generate a number of different designs within a language (Figure 2).

Creativity in rule-based design lies in the creation of the rules. Rules can be modified and expanded at every stage of a design process allowing the designer to make explicit his/her design knowledge in a structured framework. The designer controls form-generation by explicitly defining the criteria for new designs that fit a given context (Çolakoğlu, 1996).

Shape grammars are derived from a given corpus of designs that include traditional Chinese lattice designs (Stiny, 1977), Palladian villa plans (Stiny and Mitchell, 1978),

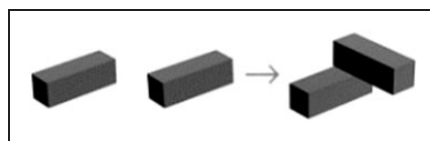


Figure 1. Shape grammar based on a vocabulary and an addition rule.

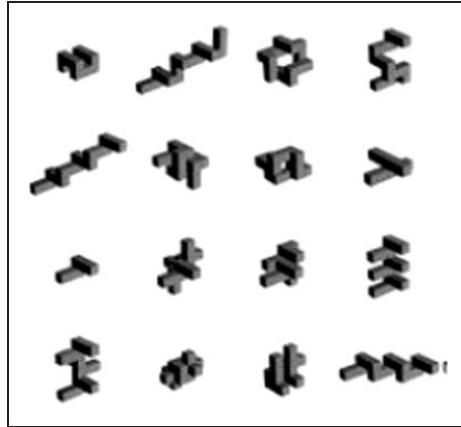


Figure 2. Sixteen different possible designs created by the shape grammar (Knight, 1999).

Mughul gardens (Stiny and Mitchell, 1980), Hepplewhite chair-back designs (Knight, 1980), Japanese tearoom plans (Knight, 1981), the architecture of Guiseppe Terragni (Flemming, 1981), bungalows of Buffalo (Downing and Flemming, 1981), the prairie houses of Frank Lloyd Wright (Koning and Eizenberg, 1981), Greek vase motifs (Knight, 1986), Queen Anne houses (Flemming, 1987), Ndebele homesteads (Herbert et al., 1994), and row-houses (Çağdaş, 1996b). The common point in all these studies is to regenerate the patterns of the products which belong to various languages of designs in a generative approach. These languages emerged as examples of vernacular architecture, neo-classical architecture, traditional garden designs, and furniture designs as well as the individual designs of some well-known architects (Çağdaş, 1996b).

For describing a spectacular example of shape grammar addition rules, Koning and Eizenberg (1981) developed the language of The Prairie Houses of Frank Lloyd Wright in 1981. They published their study on the Prairie House language, developing an extremely detailed grammar with which it is possible to generate all the houses designed by Wright and many more in the style (Figure 3).

Shape grammars have been used in architecture to generate alternatives and variations of specific architectural models. A set of geometric rules describes a specific architectural style and can be applied step by step to create new designs.

Problem definition

As we explained above, producing plans for stores is crucial in today's world. Prioritizing the plans that produced with shape grammar (Ozdemir, 2014) was chosen for this study and fuzzy AHP and fuzzy ANP approaches were used. We asked three sector experts (namely store owner, architect, and designer) about the problem of determining the best plan alternative. Three main criteria, eight sub-criteria and three alternatives were determined and weighted accordingly.

In the numerical example, the store owner, the architect, and the designer need to determine the best plan alternative for a store with three dead-walls located in a shopping mall. For this problem, decision criteria and alternatives were defined by experts, as seen in Figure 4. In this paper the main criteria are store presentation area features, store retail area features, and store–customer relationship. The arrows in Figure 4 represent the hierarchy of the problem.

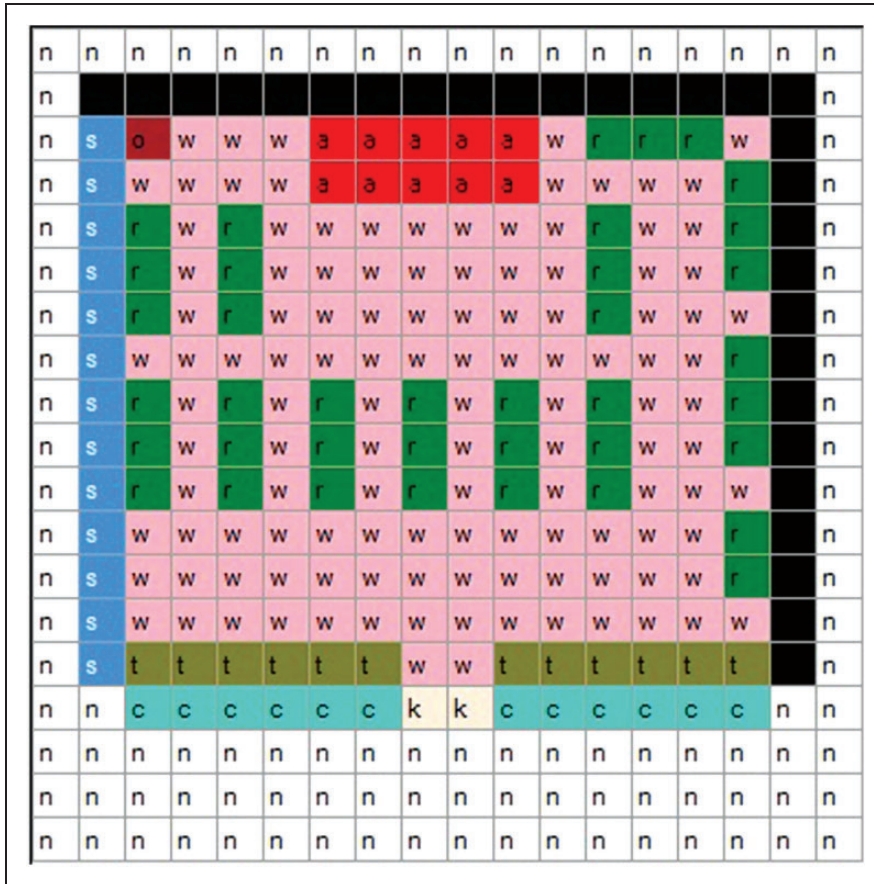


Figure 5. Alternative A1 produced with shape grammar (Ozdemir, 2014).

and black cells, the character “c” represents the window, “t” is for the shopwindow-exhibit, “r” is for the interior-exhibit, “a” is for the cashier and the warehouse, and lastly “o” is for the changing room for customers (Ozdemir, 2014).

Fuzzy AHP methodology

AHP is one of the common methods with which MCDM problems can be solved. The decision problem is structured hierarchically at different levels in this methodology (Mikhailov, 2003). The local priorities in AHP are established using pairwise comparisons and judgments (Promentilla et al., 2008). The priorities in the AHP are assessed indirectly from pairwise comparisons judgments (Mikhailov, 2003).

AHP had been applied in a variety of contexts: from the simple everyday problem of selecting a school to the complex problems of designing alternative future outcomes of a developing country, evaluating political candidacy, allocating energy resources, and so on (Ozdoglu and Ozdoglu, 2007).

To have a significant impact on the performance of the building with respect to the various design criteria, Nassar et al. (2003) developed a computer tool for selecting the

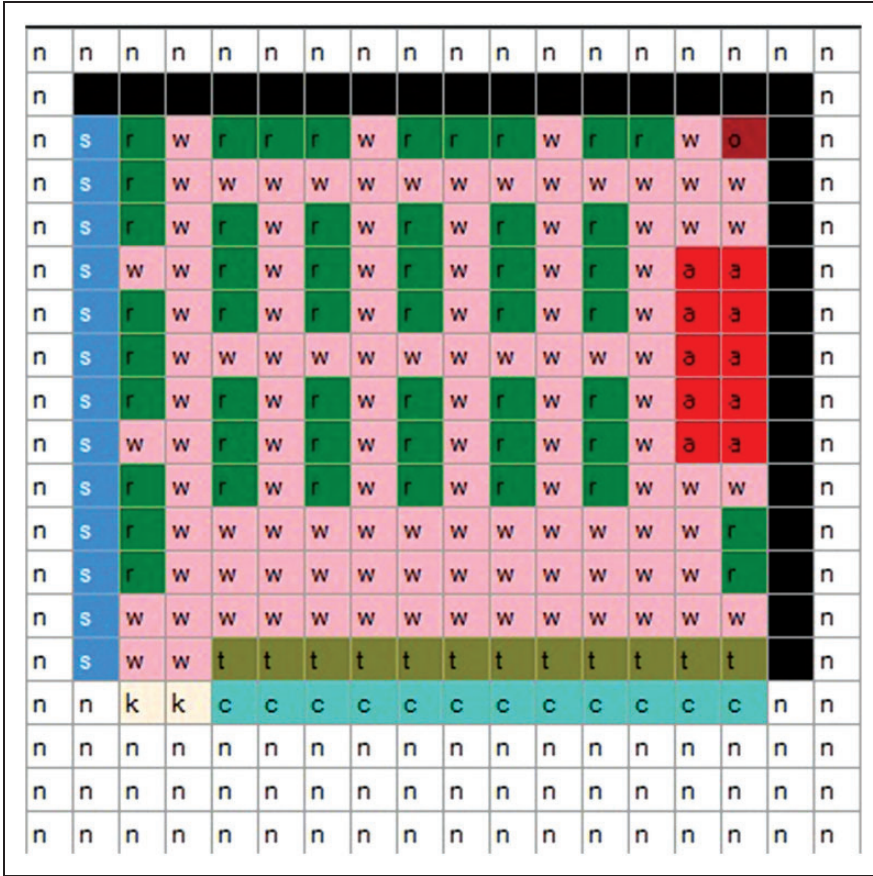


Figure 6. Alternative A2 produced with shape grammar (Ozdemir, 2014).

best combination of building assemblies for each particular design situation. They used AHP to determine the relative importance weights for the different criteria.

To select equipments for construction projects Shapira and Goldenberg (2005) presented a selection model based on AHP with a view to providing solutions for the systematic evaluation of soft factors, and the weighting of soft benefits in comparison with costs.

Bitarafan et al. (2012) selected the appropriate method which can consider all the criteria of reconstructing the damaged areas that can be useful for decision makers in managing crises. They introduced the AHP method for calculating the relative importance of the criteria and their weights.

The fuzzy AHP technique can be viewed as an advanced analytical method developed from the traditional AHP. The AHP’s subjective judgment, selection and preference of decision-makers have great influence on the success of the method. The conventional AHP still cannot reflect the human thinking style. Avoiding these risks on performance, the fuzzy AHP, an extension of AHP with fuzzy numbers, was developed to solve the hierarchical fuzzy problems. Buckley extended Saaty’s AHP to the case where the evaluators are allowed to employ fuzzy ratios in place of exact ratios to handle the difficulty for people to assign exact ratios when comparing two criteria and derive the fuzzy weights of criteria by geometric mean method (Hsieh et al., 2004).

n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
n																	n
n	s	r	r	r	w	r	r	r	w	r	r	r	w	r	r		n
n	s	w	w	w	w	w	w	w	w	w	w	w	w	w	w		n
n	s	o	w	w	r	w	r	w	r	w	r	w	r	w	r		n
n	s	a	a	w	w	w	w	w	w	w	w	w	w	w	r		n
n	s	a	a	w	r	w	r	w	r	w	r	w	r	w	r		n
n	s	a	a	w	w	w	w	w	w	w	w	w	w	w	w		n
n	s	a	a	w	r	w	r	w	r	w	r	w	r	w	r		n
n	s	a	a	w	w	w	w	w	w	w	w	w	w	w	r		n
n	s	w	w	w	r	w	r	w	r	w	r	w	r	w	r		n
n	s	r	w	w	w	w	w	w	w	w	w	w	w	w	w		n
n	s	r	w	r	w	r	w	r	w	r	w	r	w	w	r		n
n	s	w	w	w	w	w	w	w	w	w	w	w	w	w	w		n
n	s	t	t	t	t	t	t	t	t	t	t	t	t	w	w		n
n	n	c	c	c	c	c	c	c	c	c	c	c	c	k	k	n	n
n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n

Figure 7. Alternative A3 produced with shape grammar (Ozdemir, 2014).

In the literature many researchers (Boender et al., 1989; Buckley, 1985a, 1985b; Chang, 1996; Laarhoven and Pedrycz, 1983; Lootsma, 1997; Ribeiro, 1996) who had studied the fuzzy AHP, had provided evidence that fuzzy AHP shows relatively more sufficient description of these kind of decision-making processes compared to the traditional AHP methods (Ozdagoglu and Ozdagoglu, 2007).

Fuzzy AHP can be used for the evaluation and ranking of alternatives (Kahraman et al., 2004; Mikhailov and Tsvetinov, 2004; Rodríguez et al., 2013). Buyukozkan et al. (2008) proposed fuzzy AHP method to evaluate e-logistics-based strategic alliance partners. Cascales and Lamata (2008) proposed fuzzy AHP for management maintenance processes where only linguistic information was available. Alias et al. (2009) used F-AHP technique to rank alternatives to find the most reasonable and efficient use of river system.

Zeng et al. (2007) presented a risk assessment methodology to cope with risks in complicated construction situations. A modified analytical hierarchy process with fuzzy numbers was used to structure and prioritize diverse risk factors. An illustrative example on risk analysis in a shopping centre was used to demonstrate their proposed methodology.

Pan (2008) presented a fuzzy AHP model to select an appropriate bridge construction method. A case study involving an actual highway project was presented to illustrate the use

of the proposed model in the paper. Also the use of the model and the capability of the model were shown with the results.

Pan (2009) presented a fuzzy AHP approach to select an appropriate excavation construction method. A case study concerning a foundation construction project was presented in the paper. The author used Buckley's fuzzy AHP approach to analyze the problem.

Nieto-Morote and Ruz-Vila (2011) presented a risk assessment methodology based on the fuzzy sets theory and on the AHP. In this paper, a problem on risk assessment of a rehabilitation project of a building had been presented as a numerical example.

Kog and Yaman (2014) analyzed 133 peer-reviewed academic studies that were published between 1992 and 2013 and classified them as contractor selection, contractor pre-qualification, and weighting criteria. According to their paper, the statistical models, fuzzy set theory, and AHP are the most preferred methods in order to solve contractor selection problem.

Taylan et al. (2014) used analytic tools to evaluate the construction projects and their overall risks under incomplete and uncertain situations. They categorized the construction projects using fuzzy AHP and fuzzy technique for order of preference by similarity to ideal solution (TOPSIS) methodologies. In their study fuzzy AHP was used to create weights for fuzzy linguistic variable of construction projects overall risk. For the application 30 construction projects were studied with respect to five main criteria: time, cost, quality, safety, and environment sustainability. Their results showed that these methodologies are able to assess the overall risks of construction projects, select the project that has the lowest risk with the contribution of relative importance index.

Andric and Lu (2016) proposed a framework of disaster risk assessment combining Fuzzy Analytical Hierarchy Process (FAHP) with fuzzy knowledge representation and fuzzy logic techniques into a single integrated approach. They applied FAHP approach to ranking risk factors since it is more systematic, accurate, and effective than traditional AHP.

In the F-AHP and F-ANP, to evaluate the decision-makers' preferences, pairwise comparisons are structured using triangular fuzzy numbers (a^l, a^m, a^u) . The $m \times n$ fuzzy matrix can be given as in equation (1). The element a_{mn} represents the comparison of the component m (row element) with component n (column element). If \tilde{A} is a pairwise comparison matrix (equation (1)), it is assumed that the reciprocal, and the reciprocal value, i.e. $1/a_{mn}$, is assigned to the element a_{nm} (Tuzkaya and Onut, 2008; Tuzkaya et al., 2010)

$$\tilde{A} = \begin{pmatrix} (1, 1, 1) & a_{12}^l, a_{12}^m, a_{12}^u & \cdots & a_{1n}^l, a_{1n}^m, a_{1n}^u \\ \left(\frac{1}{a_{11}^u}, \frac{1}{a_{11}^m}, \frac{1}{a_{11}^l}\right) & (1, 1, 1) & \cdots & a_{2n}^l, a_{2n}^m, a_{2n}^u \\ \vdots & \vdots & \vdots & \vdots \\ \left(\frac{1}{a_{1n}^u}, \frac{1}{a_{1n}^m}, \frac{1}{a_{1n}^l}\right) & \left(\frac{1}{a_{2n}^u}, \frac{1}{a_{2n}^m}, \frac{1}{a_{2n}^l}\right) & \cdots & (1, 1, 1) \end{pmatrix} \quad (1)$$

Zadeh (1965) introduced the fuzzy set theory to deal with the uncertainty due to imprecision and vagueness. A major contribution of fuzzy set theory is its capability of representing vague data. A triangular fuzzy number is defined as (l, m, u) , where $l \leq m \leq u$, denote the smallest possible value, the most promising value and the largest possible value.

The steps of fuzzy AHP can be listed as follows (Hsieh et al., 2004; Kaya and Kahraman, 2011):

Step 1: Determine the alternatives, criteria, and subcriteria to be used in the model.

Step 2: Create a hierarchy including goal, criteria, subcriteria, and alternatives.

Step 3: Evaluate the relative importance of the criteria using pairwise comparisons. Assign linguistic terms to the pairwise comparisons by asking which criterion is more important than the other with fuzzy numbers

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & \dots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \dots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \dots & 1 \end{bmatrix} \quad (2)$$

$$= \begin{bmatrix} 1 & \tilde{a}_{12} & \dots & \tilde{a}_{1n} \\ 1/\tilde{a}_{12} & 1 & \dots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/\tilde{a}_{1n} & 1/\tilde{a}_{2n} & \dots & 1 \end{bmatrix} \quad (3)$$

Step 4: Define the fuzzy geometric mean and fuzzy weight of each criterion

$$\tilde{r}_i = (\tilde{a}_{i1} \otimes \tilde{a}_{i2} \otimes \dots \otimes \tilde{a}_{in})^{1/n}, \quad \tilde{w}_i \quad (4)$$

$$= \tilde{r}_i \otimes (\tilde{r}_1 \oplus \dots \oplus \tilde{r}_n)^{-1} \quad (5)$$

where \tilde{a}_{in} is the fuzzy comparison value of criterion i to criterion n , thus, \tilde{r}_i is the geometric mean of fuzzy comparison value of criterion i to each criterion, \tilde{w}_i is the fuzzy weight of the i th criterion.

Step 5: Defuzzify and normalize the fuzzy weights.

Fuzzy ANP methodology

ANP is a generalization of the AHP which can take the inner and outer dependencies among multiple criteria into consideration. ANP is used to determine the priorities of the elements in the network and the alternatives of the goal. ANP allows modeling complex and dynamic environments which are influenced by changing the external factors (Meade and Sarkis, 1998). ANP is an excellent methodology which can deal with several issues by considering dependencies between nodes and clusters of criteria (Öztayşi et al., 2011).

Buckley's fuzzy AHP algorithm (Haghighi et al., 2010; Hsieh et al., 2004; Kaya and Kahraman, 2011) based fuzzy ANP is used for selecting the best plan alternative produced with shape grammar (Ozdemir, 2014) in this paper. Fuzzy ANP allows measuring qualitative factors by using fuzzy numbers instead of crisp values in order to make decisions easier and obtain more realistic results (Öztayşi et al., 2013).

In the literature, the fuzzy ANP method has been used to solve problems like research and development project selection (Mohanty et al., 2005), performance evaluation (Yellepeddi, 2006), quality function deployment implementation (Ertay et al., 2005), enterprise resource planning (ERP) software selection (Ayag and Ozdemir, 2007), tourism type prioritization (Demirel et al., 2010), etc.

Öztayşi et al. (2011) compared the customer relationship management (CRM) performances of e-commerce firms using a MCDM approach—ANP. A sensitivity analysis was also provided in order to monitor the robustness of the proposed ANP framework to changes in the weights of evaluation criteria. Their results showed that the ranking among the alternatives are sensitive to changes in the parameters.

Tuzkaya et al. (2010) proposed an integrated fuzzy MCDM methodology for selecting material handling equipment. The proposed approach utilizes fuzzy sets, ANP, and the preference ranking organization method for enrichment evaluations (PROMETHEE).

Tuzkaya and Onut (2008) proposed a model for selecting the most convenient transportation mode by considering the effects of criteria on the alternative modes and relations among the criteria clusters and subcriteria using fuzzy ANP.

Buyukozkan et al. (2004) used fuzzy ANP to prioritize design requirements by taking into account the degree of the interdependence between customer needs and design requirements and their dependence.

Ebrahimnejad et al. (2012) studied a construction project problem with multiple criteria in a fuzzy environment and proposed a new two-phase group decision-making approach. This approach integrated a modified ANP and an improved compromise ranking method, VIKOR.

Zhou et al. (2013) proposed a flexibility measurement model of enterprise resources planning (ERP) based on a FANP. Hung et al. (2012) applied the FANP model to evaluate the strategic impact of new integrated circuit (IC) manufacturing technologies within Taiwan's packaging industry.

The steps of fuzzy ANP can be listed as follows (Yasmin et al., 2013):

- Step 1: Determine the alternatives, criteria, and subcriteria to be used in the model.
- Step 2: Create a network including alternatives, criteria, subcriteria, inner, and outer dependencies among the model.
- Step 3: Construct pairwise matrices of the components by the experts with fuzzy numbers.
- Step 4: Construct the fuzzy comparison matrix by using triangular fuzzy numbers.
- Step 5: Calculate fuzzy eigen value to find whether the constructed matrix is consistent or not.

To verify the consistency of the comparison matrix, Saaty proposed a consistency index (C.I.) and consistency ratio (C.R.). The consistency index of a matrix is given by

$$C.I. = (\lambda_{\max} - n)/(n - 1) \quad (6)$$

$$C.R. = C.I./R.I \quad (7)$$

where R.I is Random Consistency Index. The consistency index should be less than or equal to 0.10.

- Step 6: Forming initial supermatrix of the network of ANP is composed by listing all nodes horizontally and vertically.
- Step 7: Obtaining weighted supermatrix by multiplying the unweighted supermatrix with the corresponding cluster priorities.
- Step 8: Calculating limited supermatrix by limiting the weighted supermatrix by raising it to sufficiently large power so that it converges into a stable supermatrix (i.e., all columns being identical).

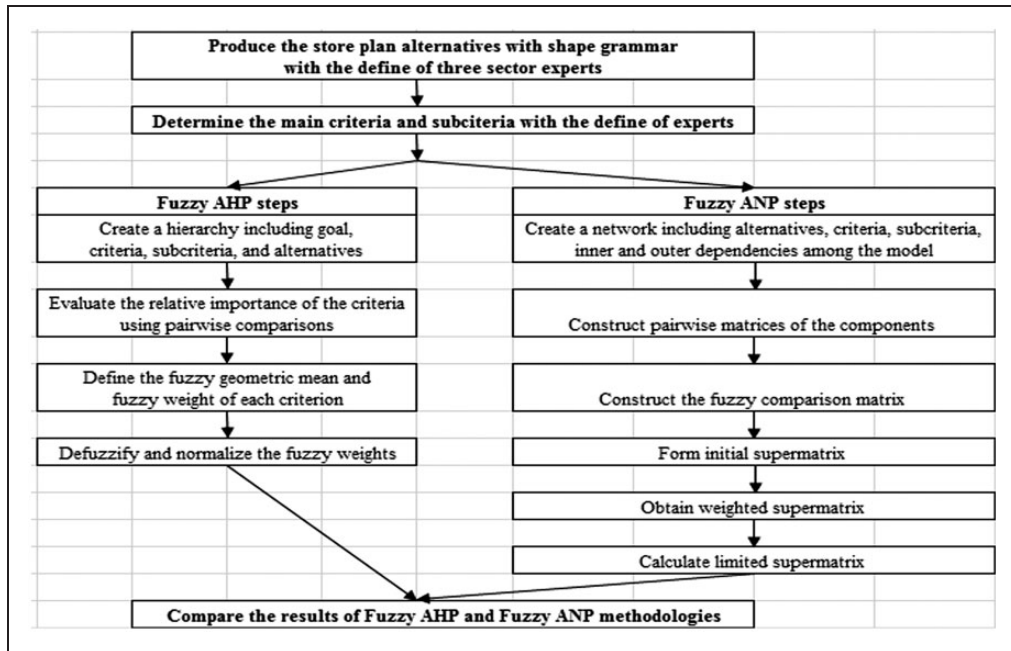


Figure 8. The layout of the application case.

Application: Evaluation of plan alternatives

In this paper we apply two MCDM methods to select the best store design alternative produced with shape grammar, namely fuzzy AHP and fuzzy ANP. Then, the obtained results of these techniques are compared. The layout of the application case can be seen in Figure 8.

Computational results of fuzzy AHP methodology

To solve the problem using fuzzy AHP, we used fuzzy numbers as shown in Table 1 and compared our results with those of experts. Evaluations of the alternatives by three experts with respect to the criteria can be seen in Table 2. The fuzzy weight matrix of the criteria according to the goal, fuzzy weight matrix of the subcriteria and fuzzy weight matrix of the alternatives with respect to each criterion are given in Tables 3, 4, and 5, respectively. The evaluation and the methodology described above produced the results shown in Table 6.

According to the results in Table 6 the ranking is obtained as $A1 > A2 > A3$.

Computational results of fuzzy ANP methodology

To solve the problem using fuzzy ANP, we used fuzzy numbers as shown in Table 1 and compared our results with those of experts. Evaluations of the alternatives by three experts with respect to the criteria, fuzzy weight matrix of the criteria according to the goal, fuzzy weight matrix of the subcriteria and fuzzy weight matrix of the alternatives with respect to each criterion were the same as the values of the fuzzy AHP that can be seen in Tables 2 to 5.

Table 1. Relationship between fuzzy numbers and degrees of linguistic importance.

Low/high levels		
Label	Linguistic terms	Fuzzy numbers
E	Just equal	(1,1,1)
SL	Slightly low	(1,1,3)
M	Middle	(1,3,5)
SH	Slightly high	(3,5,7)
H	High	(5,7,9)
VH	Very high	(7,9,9)
EH	Extra high	(9,9,9)

Table 2. Average values used in fuzzy AHP and fuzzy ANP.

Criteria	Importance value	L			M			U			E1			E2			E3		
		L	M	U	L	M	U	L	M	U	L	M	U	L	M	U			
C1	EH	9	9	9															
c11	VH	7	9	9	EH	9	9	9	EH	9	9	9	VH	7	9	9			
c12	VH	7	9	9	EH	9	9	9	VH	7	9	9	EH	9	9	9			
c13	VH	7	9	9	EH	9	9	9	VH	7	9	9	EH	9	9	9			
C2	EH	9	9	9															
c21	VH	7	9	9	EH	9	9	9	EH	9	9	9	VH	7	9	9			
c22	H	5	7	9	EH	9	9	9	EH	9	9	9	H	5	7	9			
c23	VH	7	9	9	EH	9	9	9	EH	9	9	9	VH	7	9	9			
C3	VH	7	9	9															
c31	VH	7	9	9	EH	9	9	9	VH	7	9	9	EH	9	9	9			
c32	M	1	3	5	EH	9	9	9	EH	9	9	9	SL	1	1	3			

Table 3. Fuzzy weight matrix of the criteria according to the goal.

	L	M	U
C1	0.26	0.33	0.58
C2	0.26	0.33	0.58
C3	0.12	0.33	0.40

Also initial supermatrix, weighted supermatrix, and the limited supermatrix can be seen from Tables 7 to 9. The evaluation and the methodology described above produced the results shown in Table 10.

According to the results in Table 10 the ranking is obtained as $A1 > A2 > A3$.

The impact of interactivity among main criteria and subcriteria in fuzzy ANP are the reason of the variations in the weights and normalized values.

Given these results, it is fair to say that selecting Alternative A1 is the most reasonable outcome, followed by the others (Table 11).

Table 4. Fuzzy weight matrix of the subcriteria.

	L	M	U
C11	0.33	0.33	0.33
C12	0.33	0.33	0.33
C13	0.33	0.33	0.33
C21	0.26	0.33	0.58
C22	0.12	0.33	0.40
C23	0.26	0.33	0.58
C31	0.65	0.88	1.17
C32	0.10	0.13	0.17

Table 5. Fuzzy weight matrix of the alternatives with respect to each criterion.

	L	M	U	L	M	U	L	M	U	L	M	U
	C11			C12			C13			C21		
A1	0.82	0.82	0.82	0.47	0.47	0.47	0.82	0.82	0.82	0.29	0.67	1.38
A2	0.09	0.09	0.09	0.47	0.47	0.47	0.09	0.09	0.09	0.10	0.24	0.66
A3	0.09	0.09	0.09	0.05	0.05	0.05	0.09	0.09	0.09	0.05	0.09	0.23
	C22			C23			C31			C32		
A1	0.61	0.79	1.00	0.62	0.75	0.90	0.62	0.75	0.90	0.17	0.33	0.42
A2	0.08	0.15	0.23	0.17	0.21	0.25	0.17	0.21	0.25	0.25	0.33	0.87
A3	0.05	0.07	0.11	0.04	0.04	0.05	0.04	0.04	0.05	0.17	0.33	0.42

Table 6. Results of the application using fuzzy AHP.

	Weights	Normalized values
A1	2.3766	69.34%
A2	0.7892	23.02%
A3	0.2618	7.64%

Table 7. Initial supermatrix.

	C11	C12	C13	C21	C22	C23	C31	C32
C11	0.00000	0.50000	0.50000	0.33333	0.33333	0.33333	0.33333	0.33333
C12	0.50000	0.00000	0.50000	0.33333	0.33333	0.33333	0.33333	0.33333
C13	0.50000	0.50000	0.00000	0.33333	0.33333	0.33333	0.33333	0.33333
C21	0.36578	0.36121	0.36121	0.00000	0.50000	0.56547	0.36121	0.36121
C22	0.26844	0.27758	0.27758	0.43453	0.00000	0.43453	0.27758	0.27758
C23	0.36578	0.36121	0.36121	0.56547	0.50000	0.00000	0.36121	0.36121
C31	0.87180	0.86775	0.86775	0.86775	0.86775	0.86775	0.00000	1.00000
C32	0.12820	0.13225	0.13225	0.13225	0.13225	0.13225	1.00000	0.00000

Table 8. Weighted supermatrix.

	C11	C12	C13	C21	C22	C23	C31	C32
C11	0.00000	0.12500	0.12500	0.08333	0.08333	0.08333	0.08333	0.08333
C12	0.12500	0.00000	0.12500	0.08333	0.08333	0.08333	0.08333	0.08333
C13	0.12500	0.12500	0.00000	0.08333	0.08333	0.08333	0.08333	0.08333
C21	0.09144	0.09030	0.09030	0.00000	0.12500	0.14137	0.09030	0.09030
C22	0.06711	0.06939	0.06939	0.10863	0.00000	0.10863	0.06939	0.06939
C23	0.09144	0.09030	0.09030	0.14137	0.12500	0.00000	0.09030	0.09030
C31	0.21795	0.21694	0.21694	0.21694	0.21694	0.21694	0.00000	0.25000
C32	0.03205	0.03306	0.03306	0.03306	0.03306	0.03306	0.25000	0.00000

Table 9. Limited supermatrix.

	C11	C12	C13	C21	C22	C23	C31	C32
C11	0.08333	0.08333	0.08333	0.08333	0.08333	0.08333	0.08333	0.08333
C12	0.08333	0.08333	0.08333	0.08333	0.08333	0.08333	0.08333	0.08333
C13	0.08333	0.08333	0.08333	0.08333	0.08333	0.08333	0.08333	0.08333
C21	0.08909	0.08909	0.08909	0.08909	0.08909	0.08909	0.08909	0.08909
C22	0.07182	0.07182	0.07182	0.07182	0.07182	0.07182	0.07182	0.07182
C23	0.08909	0.08909	0.08909	0.08909	0.08909	0.08909	0.08909	0.08909
C31	0.17105	0.17105	0.17105	0.17105	0.17105	0.17105	0.17105	0.17105
C32	0.07895	0.07895	0.07895	0.07895	0.07895	0.07895	0.07895	0.07895

Table 10. Results of the application using Fuzzy ANP.

	Weights	Normalized Values
A1	1.0000	65.23%
A2	0.3548	23.14%
A3	0.1782	11.62%

Table 11. Comparison of the results using fuzzy AHP and fuzzy ANP.

	Weights		Normalized values	
	Fuzzy AHP	Fuzzy ANP	Fuzzy AHP	Fuzzy ANP
A1	2.3766	1.0000	69.34%	65.23%
A2	0.7892	0.3548	23.02%	23.14%
A3	0.2618	0.1782	7.64%	11.62%

Conclusion

In this paper, multi-criteria decision-making techniques, fuzzy AHP, and fuzzy ANP methods are used for the evaluation of store plan alternatives that were produced with shape grammar. Then, the obtained results of these techniques are compared. As a result of evaluation process, these two MCDM methods, fuzzy AHP and fuzzy ANP, have determined the most suitable result as A1. The ranking of the other alternatives are $A2 > A3$ in both methods with close weights and normalized values.

The impact of interactivity among main criteria and subcriteria in fuzzy ANP is the reason for the variations in the weights and normalized values. The main advantage of the proposed model is to indicate the impact of this interactivity and to evaluate the shape grammar plan alternatives using MCDM. The main contribution of this paper is to prioritize plan alternatives using numerical methods with experts' view.

The general limitation of the proposed model is the costly and exhausting information requested from experts (approx. 90 pairwise comparisons per one expert). Other limitations of the model are the preferences of the expert including uncertainty and conflicts and there is often a need for more than one expert to make decisions.

As regards future research, plan alternatives produced with other computer-aided architectural design method—cellular automata—and also hybrid methods could be evaluated by these MCDM techniques. On the other hand, the problem could be solved by other MCDM techniques with fuzzy numbers to explain interactivity among main criteria and subcriteria, and more solutions compared for plan alternatives evaluation processes. Also, intelligent software to calculate solutions automatically could be developed.

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