Space Ontology International Journal
ISSN: 2345-6450
OISSN: 2423-7299
Journal homepage: soij.qiau.ac.ir
Winter 2025, Vol. 14, Issue 1, No. 52, Pages: 43-56

Fuzzy Logic-Based Model for Evaluating Architectural Space Quality

Mansoureh Sadrykia [a], Somayeh Sadrykia [b,*]

[a] Deptartment of Geomatics Engineering, Faculty of Civil Engineering, University of Tabriz, Tabriz, Iran
[b] Department of Architecture, Urbanism and Art, Urmia University, Urmia, Iran

Received: 25 September 2024.- Accepted: 13 March 2025
Doi: 10.71879/soij.2025.1185137

Abstract

Considering the significance of architectural space quality in human beings lives and the multi-faceted nature of its indicators, there is a need for scientific and reliable methods for modeling space quality that widely integrate and evaluate affecting indicators. Despite the effective role of space quality indicators' importance in promoting architectural designs, researchers have not yet studied various criteria involved in evaluating architectural space comprehensively. Despite the necessity of taking into account all aspects of space quality for specifying a complete set of influencing criteria and accordingly determining the importance of the considered criteria for creating desirable space quality, this issue has not yet been considered well in previous studies. Currently, architects rely on professional expertise to enhance space quality. However, a mathematical model that systematically evaluates qualitative criteria can serve as a more objective tool for optimizing design outcomes. Fuzzy sets theory provides an efficient tool for considering vagueness uncertainties of the professionals' knowledge in a mathematical framework guaranteeing that outcomes of space evaluation will be concrete and reliable. The novelty of present study includes a) integrating different aspects of space quality in one space evaluation model, b) considering and modeling the fact that some criteria are related to more than one quality indicator and c) considering that expertise on influencing criteria weights of importance are qualitative judgments that include vagueness uncertainty, utilizing fuzzy sets theory to model the uncertainty quantitatively and mathematically. We first studied the most important quality criteria defined by scholars and discussed major relevant criteria. We showed that quality of architectural space have three main indicators, each with various criteria. The weights of the criteria in each indicator were categorized into low, medium and high level. Using fuzzy sets theory the most influential criteria relevant to each of main quality indicators were determined. Among the specified 30 crucial quality criteria, "legibility", "visual clarity", "hierarchy", "objective transparency", and "diversity" had the highest importance for more than one indicator. Therefore, it can be concluded that they play a more significant role in creating space quality. Finally, we presented a fuzzy space quality evaluation conceptual model. The presented model provides architects with a set of helpful design rules that would enable them to reliably consider the effects of each space quality criterion to design more desirable architectural spaces for users. This study can be a guide for planners, designers, managers and policy makers engaged in designing and assessing various spaces.

Keywords: Fuzzy Sets; Architectural Quality; Space Evaluation; Qualitative Criteria.

1. Introduction

The need for shelter and protection are the critical requirements of humans. Architectural spaces are developed to fulfill this need. It is a limited part of nature perceived by humans. An architectural space is introduced as a limited part of the world perceived by observers (Simpson et al., 1993; Sozen & Tanyeli, 1994). An architectural space can be clear and specific but with vague boundaries, which would cause much uncertainty for architects (Arabacioglu, 2010). In the process of architectural space design, architects form many spaces, considering the various space uncertainties involved, therefore the success of architects' designs is based on their professional and experiential knowledge (Atman et al., 2005). Although in the present age improving space quality to meet space desirability is a vital issue of designing and planning spaces, the knowledge and experience of the architects in creating space quality have intuitive and vague nature. The significance of space quality and the multitude of its indicators have necessitated a reliable space quality modeling that would systematically evaluate all the indicators affecting it. However, a comprehensive investigation of the whole indicators raised by scholars considering different aspects of space quality has not been taken into account yet.

This paper aims to propose a new space quality evaluation model. By considering the nature of space quality, we proposed using fuzzy sets theory as a valuable method for space quality evaluation. Using this method, the degree of membership of various quality sub-criteria can be included mathematically in the model. The obtained space quality evaluation model enables architects to design a more desirable architectural space for users by bringing in reliable and tangible effects of each quality criterion.

The study questions are: a) What are the different space quality criteria? b) How are the different criteria classified? c) How important are each of the space quality criteria? d) Which method can efficiently weigh the influence of the sub-criteria of space quality? In this regard, the main question is that considering the vague nature of space quality and the need to determine affecting criteria and weigh the importance of different sub-criteria, what model will be suitable for evaluating the quality of architectural space?

* Corresponding Author Email: s.sadrykia@urmia.ac.ir

The main hypothesis is that fuzzy set theory can be used to provide a model of architectural space quality in which, the importance of various criteria are specified using a degree of membership to the quality indicators. The proposed model not only helps to evaluate the quality of existing spaces, but also to provide different alternatives before the space design stage which enables the designers to achieve quality type that they intend for their plan by considering ranks of criteria determined.

To achieve the goal of this research, the steps of the study are as follows: First, we examine the critical definitions of quality and its indicators. We classify the qualitative criteria into different sub-criteria. The sub-criteria were then ranked using the opinions of the experts. Fuzzy set theory was used to assign weights to criteria_ belonging to each of the main quality types. Finally, this study presented an integrated fuzzy evaluation model of space quality.

2. Literature Review

There are various studies conducted in the field of quality in architecture and urban planning. These studies can be categorized as below based on the topic of discussion and study method (in order from most abundant to least abundant): "quality, "quality in architecture", "fuzzy logic in architecture" and "fuzzy logic in architectural space quality modeling". In the following, we introduce examples of studies for each category.

A) **Quality studies:** Relatively extensive studies have examined quality from a macro level at a city or neighborhood scale (Carmona, 2010; Thomson et al., 2003; Billing, 1993). These studies mainly use statistical analytical models and GIS software. These studies mainly consider few and general levels of quality criteria such as design, maintenance, activities and safeties (Aşilioğlu et al., 2020), while the present study takes into account comprehensive levels of quality that affect architectural spaces, not only in macro level but in different scales.

B) **Quality studies in architecture:** Few studies have investigated the issue of quality in architecture (Eilouti, 2020; Harputlugil et al., 2016; Rapoport, 1970). For example, a study has discussed the use of fuzzy logic in identifying the criteria affecting the quality of buildings' design (Nazari & Torabi, 2022). A review study has evaluated housing environment quality using a multi-criteria analysis, including energy efficiency (Mazur et al., 2022). Their study focus on limited quality determinants like; energy efficiency, thermal comfort, sustainable heating, and ventilation, aiming to improve only the energy efficiency of buildings, so they just considered the environmental aspects of quality. The evaluation of the design quality by scoring quality of student housing facilities in a university campus is another example (Sanni-Anibire & Hassanain, 2016). Some research investigated the quality of architecture from a specific perspective. For example, the quality of architecture in residential areas was studied from real estate management point of view (Nordwall & Olofsson, 2013). In an article, the integration of design quality with education quality in future schools was examined from the users' point of view (Stringer et al., 2012). Another research employs an interdisciplinary methodology to investigate how Scio-cultural factors affect the quality of public open spaces (Anuar et al., 2024). This study reveals some quality factors like availability of cultural events, safety and comfort as quality criteria of public open spaces. It can be seen that although these studies mentioned some architectural quality criteria but most of them are about a specific place or context or architectural elements like façade. In contrast, our study tries to investigate and consider a vast quality criteria set usable for most types of architectural context and/or spaces.

C) **Fuzzy logic in Architecture:** Architectural research have mainly used non-fuzzy methods. Some studies concerning the use of fuzzy logic in architecture follows. A study suggested fuzzy logic approach as framework for the automatic evaluation of architectural spatial configuration (Nady et al., 2023). Another study used fuzzy inference systems for architectural spatial analyses (Arabacioglu, 2010). Another study used fuzzy logic in the design process of a school classroom (Diker & Erkan, 2022). Bostancioglu (2021) used fuzzy set theory to evaluate building facade systems such as two-shell façade. Although taking into account quality criteria weights is essential for designing optimal architectural spaces, these types of studies do not consider the importance of weighing quality criteria in designing various types of spaces. However, using fuzzy sets theory provides a proper tool for quantifying degree of importance of each quality criterion.

D) **Fuzzy logic in modeling the quality of architectural spaces:** In this context, fuzzy logic has been studied only from specific aspects, as a component, for example, the evaluation of the light inside the office (Zemmouri & Schiler, 2005), aesthetics (Nadin, 2018) or automatic evaluation of spatial layout configurations using fuzzy logic (Ezzeldin et al., 2021) or establishing a framework for sustainable development assessment of a smart city (Shao et al., 2023). In the latter study an assessment framework was proposed considering environmental dimensions subdivided into multiple indicators. Fuzzy based decision – making then clarified the influence of indicators and the relationships among them. The difference of the mentioned study with the present work is that the proposed framework is not limited to sustainable performance of a smart city. The presented conceptual model in our study provides a guideline for improving architectural space quality from the perspective of formal, functional and perceptual dimensions. Another study (Naghibi Iravani et al., 2024) used Analytical Hierarchy Process (AHP) for weighing a limited number of quality criteria, without considering category of each criterion, for residential spaces of Arak City. In the next step they gathered and processed the opinions of end users about the scoring the quality of four buildings in the case study using fuzzy sets.

Although taking into account all aspects of space quality for specifying a comprehensive set of influencing criteria and accordingly determining the importance of each of the considered criteria is necessary for creating optimal space quality, according to the literature review this issue has not yet been considered nor presented. On the other hand, currently, architects rely on professional expertise and experience to enhance some aspects of space quality. However, a mathematical model that reliably and systematically evaluates quality criteria can serve as a more objective tool for optimizing design outcomes. This paper presents how to consider and transfer qualitative influencing criteria in a mathematical framework for optimum architectural quality modeling. Fuzzy sets theory is utilized as needed tool for quantitative modeling of importance of influential criteria, which are inherently vague. Fuzzy sets theory can model existing vagueness uncertainty of weighing qualitative criteria efficiently and reliably. The application of fuzzy sets for this issue has not been previously considered. Finally an appropriate conceptual model is provided based on the outcomes that can be useful to make the desired quality of various architectural spaces based on the aims of designers reliably.

3. Research Methodology

The present study assumes quality as a multi-valued concept, therefore multi-valued epistemology is preferable to the two-valued epistemology. Saying that some indicators create quality in the space or not is a general statement and far from reality, so for a more realistic formulation of the quality of the space, we need to use fuzzy logic that propositions are not only 'yes' or 'no', but a range of values between 0 and 1. In this research, assuming that each of the criteria of the architectural space quality has an uncertain, relative, and graded effect, and at the same time integrated, the theory of fuzzy sets, first developed by Zadeh (1965), is used.

This article uses a qualitative method and logical reasoning strategy in a systematic structure. We examine issue of quality and its most essential indicators first. After re-reading and extracting the important indicators, critical indicators are categorized into three classes. Then classification of space quality criteria pertinent to the space quality indicators is discussed.

In the next step, a questionnaire is prepared for interviewing with experts who rank different criteria by using linguistic variables. The obtained results were analyzed using fuzzy sets theory and the weights of the quality criteria were determined. Finally, a model for evaluating space quality that shows the importance of each influencing criteria has been developed (Figure 1).

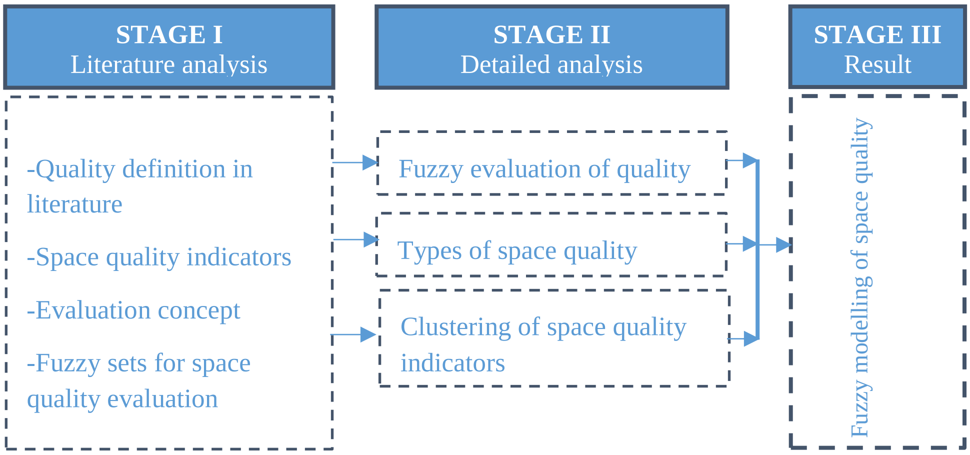


Fig. 1. Research stages

To clarify the methodology structure of the present research, a detailed framework is illustrated in Figure 2.

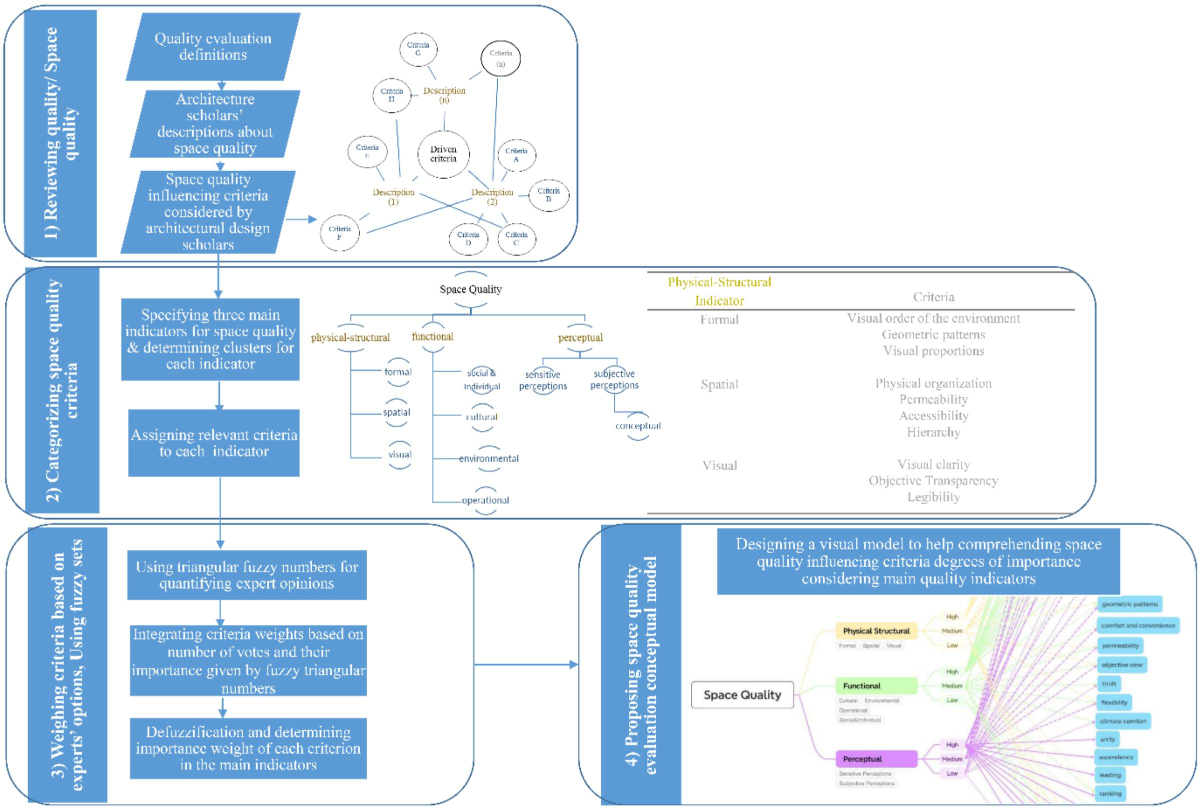


Fig. 2. Research methodology structure diagram

4. Theoretical Framework

4.1 Quality

By studying the root and lexical meaning of the word "quality" we can conclude that quality is an idea of "how" that indicates the "nature and characteristics of things"(Billing, 1993). In many descriptions, quality is a set of certain features or characteristics that distinguish one object from other objects and enable us to judge the superiority, inferiority, or similarity of something compared to another, from the aesthetic point of view, judge whether it is beautiful or ugly, good or bad, and from functionality point of view, whether it is efficient or inefficient (Golkar, 2007). The word quality indicates how much the product has met the requirements (Voordt, 2005). Some experts evaluate the quality according to the users' expectations and interpret the good quality as the degree of compliance with the standards compatible with the users. In this interpretation, the quality of a man-made phenomenon refers to the degree and extent to which that phenomenon meets the users' expectations (Montgomery, 2019). According to other researchers, quality refers to a set of inherent characteristics and attributes of anything that can meet the needs and obtain the implicit satisfaction of users (Montgomery, 1998).

According to Heft (2001) features such as mass, number, and position which are the same for different perceivers, are called "objective qualities" and features that are different to different people, are called "subjective quality".

In philosophy, "quality" is known as the nature and identity of objects and affairs, and its concept is explained in two areas, "objective", and "subjective". In this attitude, both aspects of quality are discussed in interaction.

4.2. Space quality

Quality in the architectural space is one of the most critical categories about the subject of design because one of the most important goals of design during different eras is the improvement of the quality of life via the improvement of the quality of living space and human activity. The improvement needs focusing on the indicators and criteria that affect space quality. In the contemporary era, various urban design and architecture experts have tried to investigate different aspects of quality of space and factors affecting it.

The most important factors formulated in this regard are physical and functional indicators, and criteria such as activity compatibility, form and function, accessibility, flexibility, diversity, vitality, social interactions, psychological and physical comfort, stability. Some of these criteria originate from higher-order indicators that must be grouped into related clusters for a better and more coherent examination. In the following, we refer to the most critical quality indicators presented by some leading experts.

Pakzad (2002) categorizes the quality of space into three main types namely 'formal quality', 'functional quality', and 'semantic quality'. According to him, the degree of consonance between the qualities of form, function, and meaning with each other also creates qualities usually raised in the discussion of compatibility, Such as compatibility between form and function or form and meaning. Golkar (2001) categorizes design quality into three indicators: "experiential-aesthetic quality", "functional quality" and "environmental quality". It seems that these components have been explained based on the "Canter" place model, which considers the urban environment as a place consisting of three dimensions: "body", "activity", and "imagination" (Canter, 1977) and adds the ecosystem dimension and environmental issues to it.

Relph (2016), in the book Place and Placelessness, listed three indicators of "body", "activity" and "meaning" as elements that shape place.

According to Carmona (2010) the quality of the environment can be classified into six leading indicators; "functional", "physical", "perceptual", "social", "visual", and "temporal". According to their study, the "perception" component includes collecting, organizing, and sensing the environment. The "meaning" dimension of space means qualities of space that have a direct effect on human perception. This dimension depends on the human interpretation of space. The "social" component, which includes the positive and negative qualities of a space from a social point of view, expresses how the space in the city responds to the presence of people in it and their different behaviors from a social point of view. Therefore, the effects of space on people's performance and how to regulate and control the behavior of residents in the environment are among the main topics of the social dimensions of a place. The "visual" dimension of the space includes the qualities that affect them when the space is seen by the attendees and observers. The "functional" dimension of the space is related to the qualities that depend on the activities in the space and the performance of the space itself. Moreover, the "temporal" indicator helps the designer in using activity and time cycles such as life during the day, night, and different seasons for using spaces.

Lang (1987), classified the quality of space, concerning human needs. For this purpose, he used the hierarchy of human needs from Maslow's point of view as the basis for classification, and considered those qualities that satisfy the "physiological" needs of the human being or the qualities that satisfy the needs of "safety and security", as well as "dependency and belonging", "respect and honor", "self-fulfillment" and finally the qualities that eliminate the need for "perception and beauty".

Among other contemporary theorists of the world who discussed the quality of space and its origins, are Moulaert, Schreurs, and Van Dyck (2011). Amos Rapoport, due to his history of studies in the field of quality and the importance of environmental quality and its impact on humans, in an article entitled "The Study of Spatial Quality" explored and examined the meaning of space and its quality. He considers the perception of the environment to be an extremely complex issue. This diversity and complexity are not only specific to the understanding of the environment and man-made space but also exist in the characteristics of the environment and how to communicate with it, as well as how to evaluate the quality of the perceived environment. In other words, the relationship between the characteristics of the environment and its perception and the way of evaluating the quality of the space is complex and diverse. This diversity is lawful; showing its discipline and rule. He also states that the interactions in the human environment are closely related to the two factors of 'understanding' and 'perception' and these factors are affected by culture (Rapoport, 1970). To better reveal the concept of space, Rapoport explains the characteristics of space, and classifies them as "symbolic space", "behavioral space", "mental space" and "sensory (emotional, visual, acoustic, smell, touch) space".

The critical point is that each of the mentioned types of space is variable and different according to different places, times, and cultures. For example, different cultures have differences and distinctions in emotional dimensions and aspects, and ignoring these distinctions will cause a wrong interpretation of the nature and quality of the environment in other cultures. Likewise, the quality of the space will have a meaning only when it is related to the use of the space (function and performance). It is possible that the rules used in long periods and by different cultures are stable and similar, so to discover the rules and systems, a sufficient number of examples should be studied and examined. The explanation of these similarities in the rules can be a starting point for presenting new hypotheses (Rapoport, 1970).

4.3. Evaluation

Evaluation is a judgment about quality, value, efficiency, and effectiveness. It is a structured and systematic interpretation that gives meaning to the actual effects or the predetermined outcomes of the designs.

Evaluation is a systematic judgment about the merit, quality, value, and importance of a subject, using a set of prescribed criteria, standards, and scales. In addition to this, evaluation can be defined as the process of observing and measuring a situation and context to determine its value and measure its quality, either through comparison with similar situations and contexts or by using existing standards (Eilouti, 2020). Also 'evaluation' is the careful and precise application of systematic methods to measure the design, implementation, improvement, or outputs of a program (Rossi et al., 2003).

In this article, according to the opinions of experts, a structured framework of criteria has been introduced as a set of standards for evaluating the quality of space.

4.4. Fuzzy sets theory

To understand fuzzy logic, one must first get acquainted with classical logic. In Aristotelian or classical logic, there are only two values for truth. In other words, classical logic deals with a two-valued system where each proposition has a value of zero (false) or one (true). It is a member of a set, or does not have a membership in that set. However, some propositions and concepts do not follow this valuation system because they are relative. Fuzzy logic is more consistent with the real world by using relative valuation for propositions and concepts.

In fuzzy logic, we think in the space of sets. Fuzzy logic is about concepts that, despite the completeness of information, cannot be simulated with classical logic.

Fuzzy logic was first proposed by Zadeh (1965) and expanded in various scientific fields.
A fuzzy set like A in a reference set like U means that for every u ϵ U, a function like μA (u) maps u to the interval (Sanni-Anibire & Hassanain, 2016). This function is called membership function A (Equation 1) (Zimmermann, 1996).

$$\mu_A : U \rightarrow [0,1] \qquad u \rightarrow \mu_A(u) \tag{1}$$

A triangular normal fuzzy number is shown as A= (a, b, c) (Equation 2).

$$\mu_A(x) = \begin{cases} \frac{(x-a)}{b-a} & a \le x \le b \\ \frac{(x-c)}{b-c} & b \le x \le c \\ 0 & otherwise \end{cases} \tag{2}$$

Figure (3) depicts the membership function of a triangular normal fuzzy number A= (a, b, c).

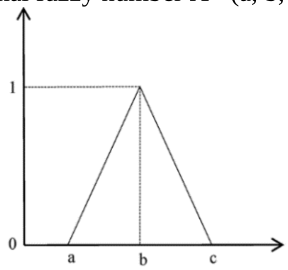


Fig. 3. Triangular normal fuzzy number

This diagram shows that "a" and "c" are not members of the set A and "b" is a member of A, and every number between "a" and "b" or "b" and "c" is a member of A to some extent (has a membership between 0 and 1).
De-fuzzification in fuzzy modeling is an essential step in which converts fuzzy values into definite or crisp values. Several methods for de-fuzzification have been proposed (Zimmermann, 1996). One is the graded mean integration technique (Chou, 2003) (Equation 3).

$$(\tilde{A}) = 1/6\ (a + 4 \times b + c) \tag{3}$$

In Equation (3) a, b, and c are the minimum value, the middle value, and the maximum value of the triangular fuzzy number A correspondingly.

5. Results and Discussion

5.1. Results

5.1.1. Types of space quality

The investigation on space quality types showed that the experts mentioned various indicators that affect the quality of the architectural space and discussed them, for example: (Appleyard & Lintell, 1972; Canter, 1977; Carmona, 2010; Chapman, 2003; Gehl, 2011; Gibson et al., 1997; Golkar, 2001; Jacob, 1961; Lynch, 1984; Moulaert et al., 2011; Moulaert et al., 2013; Punter & Carmona, 1997; Rapoport, 1970; Tibbalds, 2012). Some of these experts have emphasized social factors and individual markers. Others have emphasized functional factors. Some others pay attention to aesthetic factors and visual and formal indicators, while others consider conceptual and perceptual factors.
According to various factors and indicators of space quality considered by different researchers, multi-sensory and multi-dimensional factors affect the quality of architectural spaces. In this research, a framework that introduces the main types of space quality in an integrated manner is provided (Fig. 4). In the proposed framework, three leading indicators, namely "Structural or (form-physical)", "Functional" and "Perceptual" are introduced. We categorized each indicator into several clusters, each of which can be related to various criteria as space quality evaluation components. The criteria affecting the quality of space pertinent to each cluster will be discussed in Section 4-1-2.

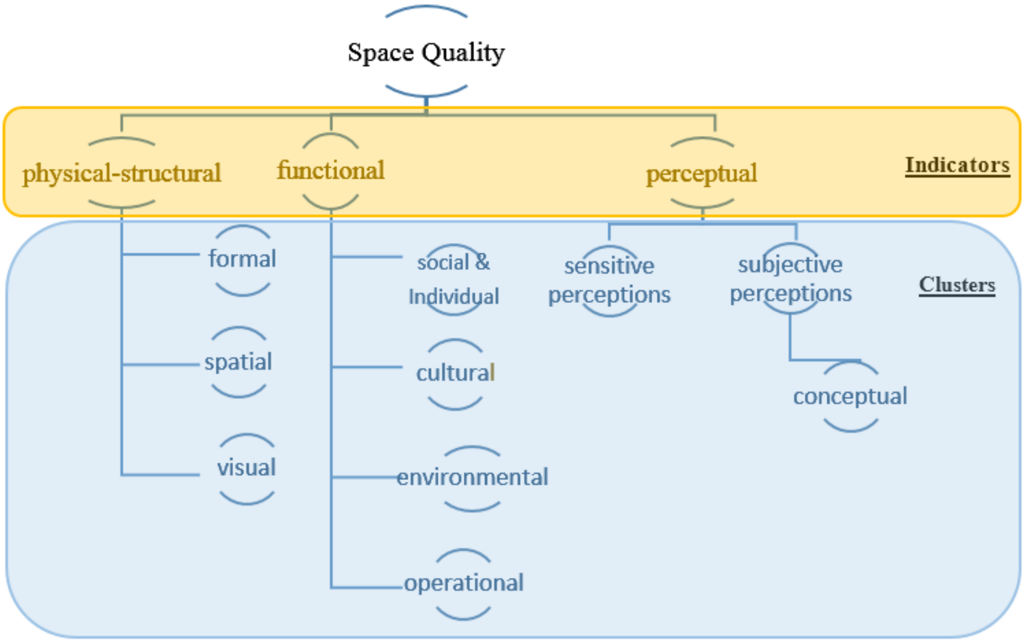


Fig. 4. Types of space quality indicators and related clusters

5.1.2. Indicators, clusters, and criteria affecting space quality

In this article, by conducting a study on the opinions of leading experts in the field of architectural design, the classification of various indicators of space quality was done according to Tables 1 to 3. The importance weights of the criteria will be discussed in the following sections.

Table 1
Proposed classification of structural indicators of space quality

Cluster	Criteria
Formal	Visual order of the environment Geometric patterns Visual proportions
Spatial	Physical organization Permeability Accessibility Hierarchy
Visual	Visual clarity Objective Transparency Legibility Variety and diversity of form

Table 2
Proposed classification of functional indicators of space quality

Cluster	Criteria
social & Individual	Human interaction with space Public spaces Flexibility Desirability of space Convenience Privacy
Cultural	Spatial justice cleanliness Visibility and privacy ranking Sense of Place
Environmental	Thrift Energy efficiency Climatic comfort Objective view
Operational	Visual clarity Visual Comfort Vision, light, and brightness Objective transparency Accessibility legibility Variety Change Movement Spatial division Order and proportions Physical organization Permeability Flexibility Hierarchy

Table 3
Proposed classification of perceptual indicators of space quality

Cluster	Criteria
Sensitive perceptions	diversity Change Visual clarity Order and proportions Visual comfort comfort and convenience Human interaction with space Geometric patterns flexibility Permeability accessibility Movement Physical organization Saving and thrift energy efficiency
Subjective perceptions	Unity ascendency leading Hierarchy ranking Sense of Place mental landscape mental comfort Spatial justice solitude visibility and privacy legibility objective transparency cleanliness Desirability of space

5.1.3. Fuzzy ranking of space quality criteria

Considering that quality is a graded matter and several factors are influential in its emergence, we examined and clustered the indicators that affect the quality of the architectural space, as explained in Section 3-3. Using the classification, valuable information can be obtained about the level of satisfaction with the design (both before and after the design).

However, due to the uncertainties in judging the quality of the space, classical logic cannot be a suitable method. By using fuzzy logic, it is possible to process non-numerical linguistic data given by users for design criteria. Thus, effective and meaningful spatial outputs are considered and provided for residents (Nadin, 2018). Therefore, the use of fuzzy sets theory was suggested in this study to provide a new model for evaluating the quality of space.

Since qualitative data and linguistic variables are closer to the human mind, questionnaires were designed based on these variables. Using Fuzzy logic to model space quality shows that each quality criterion cannot be a member of one of the quality indicators, but also belongs to other types of quality (or indicators) with different degrees of membership.

There are different types of fuzzy numbers, such as trapezoidal or triangular fuzzy numbers. In this paper for the aim of simplicity, triangular fuzzy numbers are implemented for fuzzification of qualitative criteria importance as shown in Table (4).

Table 4
Linguistic variables to determine the importance of each criterion

Linguistic variables to express importance	Triple fuzzy numbers
low	(0.1, 0.3, 0.5)
medium	(0.3, 0.5, 0.7)
high	(0.5, 0.7, 0.9)

For de-fuzzification stage (i.e. transforming fuzzy outcomes into ordinary numbers), the graded mean integration technique has been used (Chou, 2003). The mathematical calculations used to rank each criterion pertinent to the three leading quality indicators, namely "structural", "functional", and "perceptual" indicators, are presented in Table (5).

Table 5
Integration of linguistic variables for scoring each of the criteria in the leading quality indicators

	Number of Scores based on fuzzy numbers (high, medium, low)			Integrated membership degrees after de-fuzzification		
Types of quality criteria in the leading quality indicators	Structural	Functional	Perceptual	Structural	Functional	Perceptual
Desirability of space	(0, 1, 5)	(0, 3, 3)	(1, 1, 3)	0.66	0.6	0.58
Objective transparency	(0, 2, 3)	(0, 0, 5)	(1, 3, 1)	0.62	0.7	0.5
Variety	(0,3,3)	(0, 1, 5)	(1, 1, 3)	0.6	0.66	0.58
Visual clarity	(0, 2, 4)	(0, 1, 5)	(1, 1, 2)	0.58	0.66	0.55
Physical organization	(0, 2, 4)	(0, 2, 4)	(3, 2, 0)	0.58	0.58	0.38
Visual order and proportions	(1, 3, 3)	(0, 2, 4)	(0, 3, 1)	0.58	0.58	0.55
Accessibility	(0, 2, 4)	(0, 1, 5)	(3, 2, 0)	0.58	0.66	0.38
Objective view	(1, 2, 3)	(0, 2, 4)	(1, 3, 1)	0.56	0.58	0.5
Geometric patterns	(1, 2, 3)	(1, 3, 1)	(1, 1, 2)	0.56	0.5	0.55
Spatial division	(0, 4, 2)	(0, 2, 4)	(3, 2, 0)	0.56	0.55	0.38
Change	(0, 4, 2)	(0, 1, 5)	(1, 1, 3)	0.56	0.66	0.58
Movement	(0, 4, 2)	(0, 3, 3)	(3, 2, 0)	0.56	0.6	0.38
Diversity	(1, 2, 3)	(0, 3, 3)	(1, 1, 3)	0.56	0.6	0.58
Visual Comfort	(1, 2, 3)	(0, 1, 5)	(1, 1, 2)	0.56	0.66	0.55
Flexibility	(1, 3, 2)	(1, 2, 2)	(1, 3, 1)	0.53	0.54	0.5
privacy	(1, 3, 2)	(0, 2, 4)	(0, 2, 3)	0.53	0.58	0.62
Public spaces	(1, 3, 2)	(1, 2, 2)	---	0.53	0.54	---
Visibility and privacy	(1, 3, 2)	(2, 1, 2)	(0, 2, 3)	0.53	0.5	0.62
Hierarchy	(1, 3, 2)	(0, 2, 3)	(0, 1, 4)	0.53	0.62	0.66
Spatial justice	---	(2, 2, 1)	(0, 2, 3)	---	0.46	0.62
Legibility	(0, 3, 3)	(0, 1, 5)	(0, 2, 3)	0.51	0.66	0.62
Human interaction with space	(0, 3, 3)	(0, 2, 4)	(1, 1, 3)	0.51	0.58	0.58
Permeability	(2, 2, 1)	(1, 2, 3)	(1, 3, 1)	0.46	0.56	0.5
Ranking	(2, 3, 1)	(1, 2, 2)	(0, 1, 4)	0.42	0.54	0.66
Cleanliness	---	(1, 1, 4)	(1, 4, 0)	---	0.6	0.46
Energy efficiency	---	(1, 0, 4)	(1, 4, 0)	---	0.62	0.46
Thrift	---	(0, 4, 2)	(1, 4, 0)	---	0.58	0.46
Climatic comfort	---	(0, 4, 2)	(1, 4, 0)	---	0.56	0.46
Comfort and convenience	---	(1, 2, 3)	(1, 1, 3)	---	0.56	0.58
Mental comfort	---	(1, 2, 2)	(0, 1, 4)	---	0.54	0.66
Sense of Place	---	(2, 1, 2)	(0, 1, 5)	---	0.5	0.66
Unity	---	---	(0, 0, 5)	---	---	0.7
Ascendency	---	---	(0, 0, 5)	---	---	0.7
Leading	---	---	(0, 0, 5)	---	---	0.7
Mental landscape	---	---	(0, 1, 4)	---	---	0.66

In Table (5), the list of quality criteria is placed in the first column. The second, third, and fourth columns, depict the number of votes assigned by experts for each criterion pertinent to each of the three main types of quality. Six experts with more than 20 years of professional expertise of lecturing at universities and working in architectural design field were selected. Their opinions about importance of each criterion pertinent to each of the three indicators were asked. The experts were allowed to assign their scores as linguistic variables 'low', 'medium' and 'high' or select 'no score' if they did not have any opinion. For example, in Table (5) triple number (0, 2, 3) in the solitude criterion, in the fourth column (Perceptual indicator), indicates the fact that three of the experts gave 'high' score, two experts gave 'medium', and none of the experts gave a 'low' score to the importance of this criterion in the perceptual indicator. Using Equation (3) the average votes based on the de-fuzzified values for high, medium, and low scores were calculated. For example, for ‘solitude’ criterion, the average was obtained as shown in Equation (4).

$$((2\times 0.5) + (3\times 0.7)) / 5 = 0.62 \quad (4)$$

The last three columns of Table (5) show final results of membership degrees of each criterion.

As shown in Table (5) we could assign a degree of membership to each criterion in each quality indicator by considering and modeling the vagueness that exist in quality evaluation. Also we considered that some criteria may be related to more than one indicator by different weights.

5.2. Discussion

Applying the theory of fuzzy sets, the degrees of membership of quality criteria in leading quality indicators were determined. Figure (5) shows the weights of different criteria in each of the leading quality indicators.

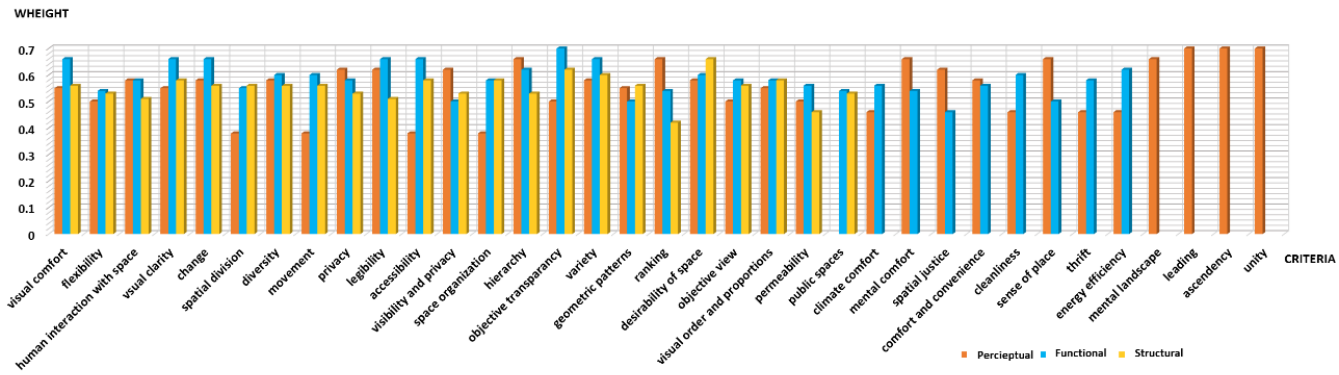


Fig. 5. Comparison of the weights of each criterion in structural, functional, and perceptual indicators

Figure (5) illustrates the weights of the criteria pertinent to the leading indicators. Besides creating a comprehensive view of all space quality criteria with different ranks, can be used in the theoretical and practical fields of design areas.

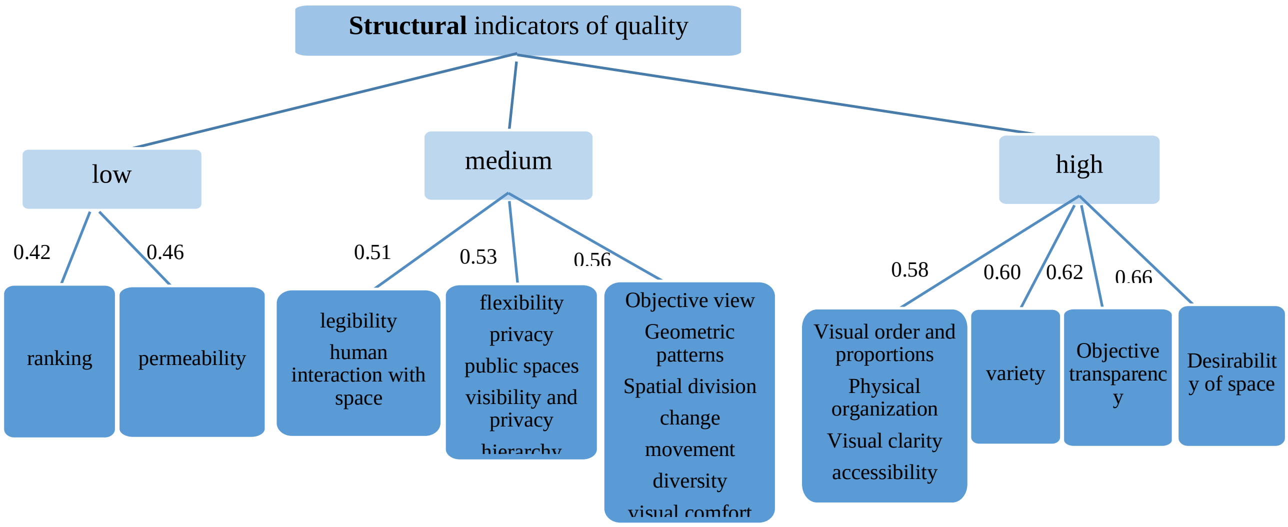
Finally, modeling the quality evaluation of the space according to three indicators: “structural”, “functional” and “perceptual” is illustrated in Figure (6). This model shows the audience the criteria with the highest degree of membership in creating each type of quality.

According to achievement of the proposed modeling, the “objective transparency, visual clarity, accessibility, legibility, variety, and hierarchy” criteria can be considered the most critical factors in creating *functional* quality. The “unity”, “ascendency”, “sense of place”, and “privacy” are the most critical criteria to create *perceptual* quality, while these criteria have little influence in creating *structural* quality. Therefore, the role of different criteria in creating different aspects of space quality is defined using the proposed model. Thereupon, designers can take into account the obtained weights of criteria for designing desirable qualities for architectural space.

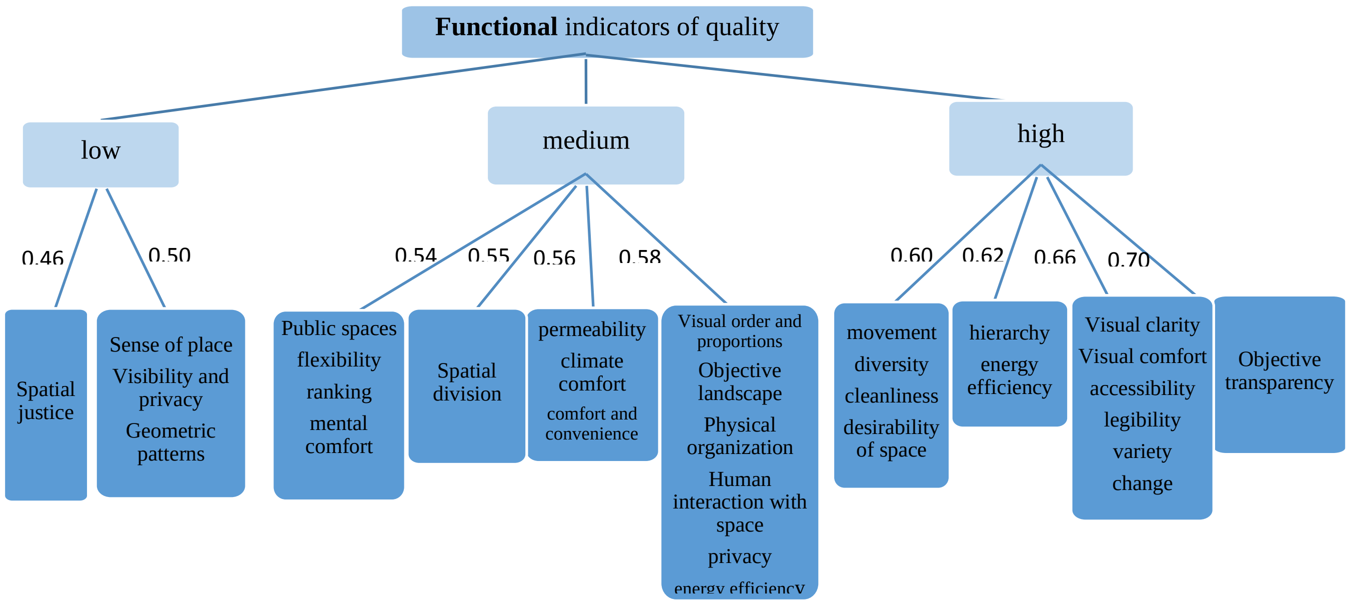
The previous studies on the field shows that there was not an existing model for integrating main aspects of quality considering various types of criteria and weighing them. Although influencing criteria weights of importance are usually presented as qualitative judgments which inherently include vagueness uncertainty, modeling this uncertainty for obtaining more accurate results of space quality evaluation was not provided in previous studies. We presented the efficiency of utilizing fuzzy sets theory to quantitatively evaluate space quality by considering and modeling uncertainties which makes the proposed model more reliable.

5.3. Conceptual model

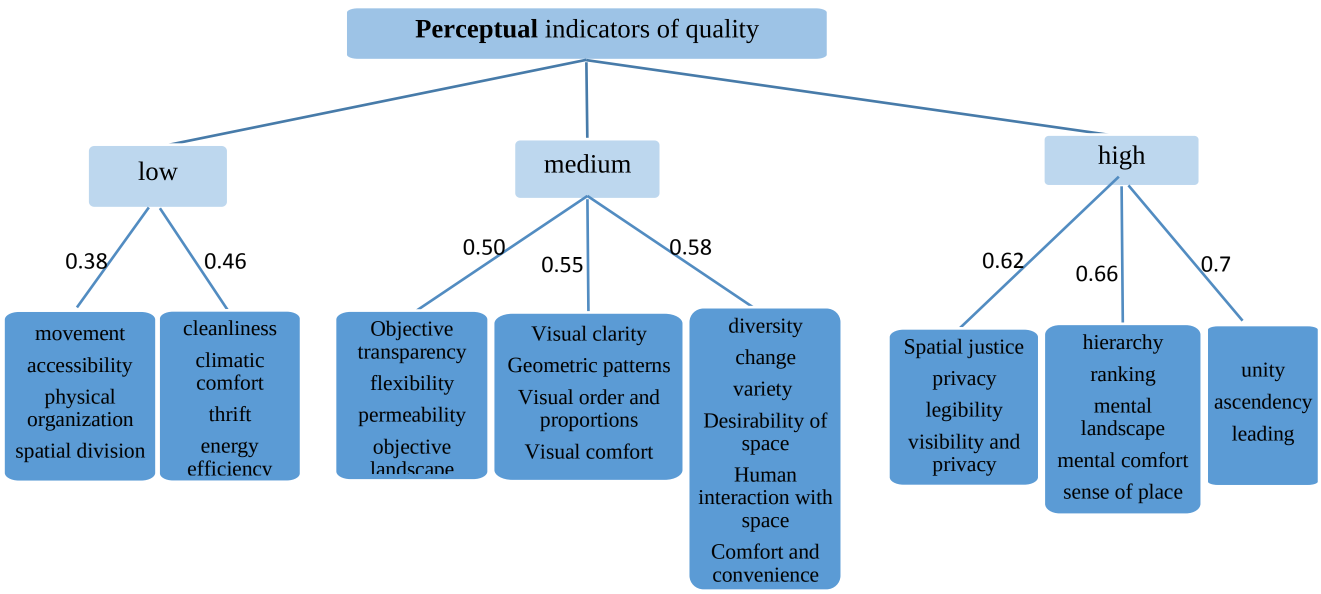
Finally, we used the obtained results to design a conceptual model for space quality evaluation. Figure (7) shows the conceptual model for all criteria and indicators. The proposed conceptual model helps to understand the influencing criteria weights considering each main quality indicator. This model provides rules that guide designers on ‘which of the criteria should be focused on and given more attention in order to create each type of space quality’. Applying the first three high weights of the criteria related to the leading indicators, guarantees the creation of desirable spaces in terms of structure, function, and perception.



a) Modeling structural quality of space



b) Modeling functional quality of space



c) Modeling perceptual quality of space

Fig. 6. Modeling the space quality (in high, medium, and low ranks) pertinent to all types of indicators

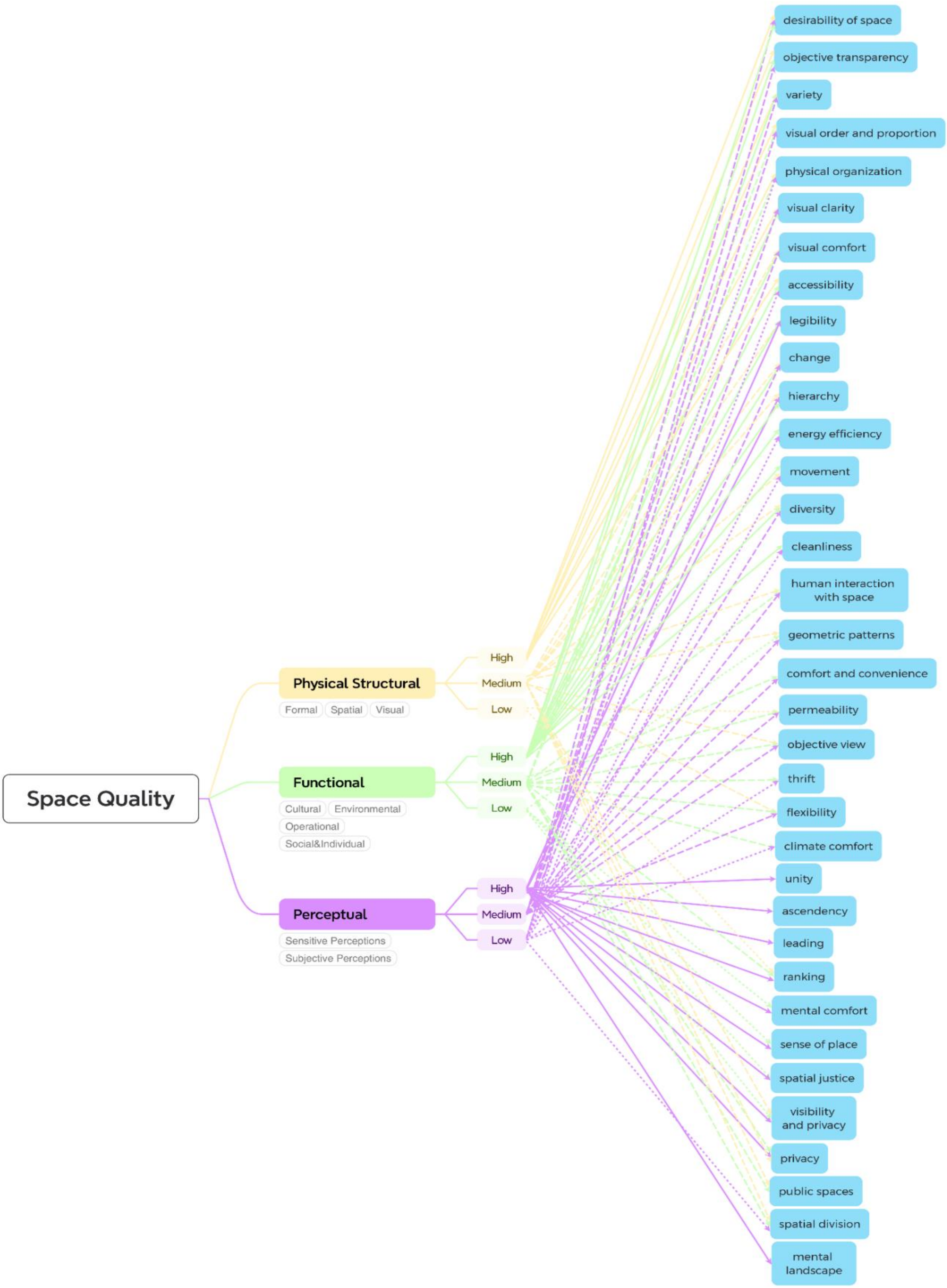


Fig. 7. Space quality conceptual model

6. Conclusion

Space quality is not an absolute concept. The presence or absence of quality in the architectural space is incorrect. Different degrees of quality exist in every space. Therefore, it does not conform to classical logic. The results of studies and research on the nature of space quality and the characteristics of the theory of fuzzy sets showed that fuzzy sets theory is suitable for analyzing and evaluating space quality. It allows processing non-numerical, linguistic expert opinion data in order to weigh the quality criteria and produce a model of quality evaluation that is meaningful and helpful for designers.

The innovations of this paper were as follows:

- From the perspective of the influencing criteria, unlike studies on urban development in neighborhood scales, the quality indicators and criteria for designing architectural spaces were investigated in this study.
- The criteria were weighted to a mathematical and numerical environment using fuzzy set theory, which is a suitable method for transferring linguistic variables used by humans to express phenomena of vague nature.
- In this article, the opinions of professional experts who work in the field of space design were used to weigh the quality criteria, and the views of the residents of architectural spaces have not been considered sufficient.
- In addition to determining the indicators and then giving weight to all the influential criteria, this article presents a conceptual model of space quality that provides architects with a set of rules for designing new spaces or evaluating existing spaces.

The degree of membership of each criterion to each of the indicators was determined in this paper using fuzzy sets. It was also showed how the space quality criteria do not individually and independently affect the space quality since they have relative, integrated, and indeterminate effects in creating different types of space quality. Finally, a conceptual model of space quality evaluation was introduced using the weighted quality criteria, which are connected. The results of this study provide a guide for planners, designers, managers and policy makers engaged in designing and/or assessing various architectural spaces. In addition this study provides a reference to follow up related research, providing a basis for making decision on assessing and designing existing or new architectural spaces. The fuzzy logic conceptual model can aid architectural designers with their current design processes by introducing most important quality criteria pertinent to each quality indicator. This guarantees the designers success in reaching desired quality aspects for the spaces that they design.

The next plan of the research is implementing the proposed conceptual model for certain case studies. The authors suggest further research to develop software based on the presented conceptual model. The provided software can help architects and designers to achieve desirable levels of space quality. Future studies may use decision making methods such as Analytic Hierarchy Processing (AHP) or Best-Worst Multi-criteria decision making (BWM) to analyze experts' opinions on the space quality criteria. Future works can be focused on analyzing other sources of uncertainty as well and modeling them in space quality evaluation.

References

Anuar, A., Mekhribanu, G., & Abdullah, A. (2024). The interrelation between socio-cultural aspects and the quality of public open spaces in Almaty, Kazakhstan. *Planning Malaysia*, *22*(33). https://doi.org/10.21837/pm.v22i33.1568

Appleyard, D., & Lintell, M. (1972). The environmental quality of city streets: the residents' viewpoint. *Journal of the American institute of planners*, *38*(2), 84-101.

Arabacioglu, B. C. (2010). Using fuzzy inference system for architectural space analysis. *Applied Soft Computing*, *10*(3), 926-937.

Aşilioğlu, F., & Çay, R. D. (2020). Determination of quality criteria of urban pedestrian spaces. *ACE: architecture, city and environment*, *15*(44). https://raco.cat/index.php/ACE/article/view/385274

Atman, C. J., Cardella, M. E., Turns, J., & Adams, R. (2005). Comparing freshman and senior engineering design processes: an in-depth follow-up study. *Design studies*, *26*(4), 325-357.

Bostancioglu, E. (2021). Double skin façade assessment by fuzzy AHP and comparison with AHP. *Architectural Engineering and Design Management*, *17*(1-2), 110-130.

Canter, D. (1977). The Psychology of Place. In: Palgrave Macmillan.

Carmona, M. (2010). Contemporary public space: Critique and classification, part one: Critique. *Journal of urban design*, *15*(1), 123-148.

Chapman, D. (2003). *Creating neighbourhoods and places in the built environment*. Taylor & Francis.

Chou, C.-C. (2003). The canonical representation of multiplication operation on triangular fuzzy numbers. *Computers & Mathematics with Applications*, *45*(10-11), 1601-1610.

Diker, F., & Erkan, İ. (2022). Fuzzy logic method in the design of elementary school classrooms. *Architectural Engineering and Design Management*, *18*(5), 739-758.

Eilouti, B. (2020). Reinventing the wheel: A tool for design quality evaluation in architecture. *Frontiers of Architectural Research*, *9*(1), 148-168.

Ezzeldin, M., Assem, A., & Abdelmohsen, S. (2021). Automated assessment of architectural spatial layout configurations using fuzzy logic. *Archnet-IJAR: International Journal of Architectural Research*, *15*(2), 328-343.

Gehl, J. (2011). Life between buildings.

Gibson, V., Rowley, A., & Ward, C. (1997). Does short termism affect the quality of urban design in the UK?

Golkar, K. (2001). Components of urban design quality.

Golkar, K. (2007). The concept of quality of life in urban design. *Safeh Quarterly*, *16*(44), 75-66.

Harputlugil, T., Gültekin, A. T., Prins, M., & Topçu, Y. İ. (2016). Architectural design quality assessment based on analytic hierarchy process: A case study. *METU Journal of the Faculty of Architecture*, *31*(2).

Jacob, J. (1961). The death and life of great American. *Cities. New York: Vintage Books*.

Lang, J. (1987). Creating Architectural Theory. In: Van Nostrand.

Lynch, K. (1984). *Good city form*. MIT press.

Mazur, Ł., Bać, A., Vaverková, M. D., Winkler, J., Nowysz, A., & Koda, E. (2022). Evaluation of the quality of the housing environment using multi-criteria analysis that includes energy efficiency: a review. *Energies*, *15*(20), 7750.

Montgomery, D. C. (2019). *Introduction to statistical quality control*. John wiley & sons.

Montgomery, J. (1998). Making a city: Urbanity, vitality and urban design. *Journal of urban design*, *3*(1), 93-116.

Moulaert, F., Schreurs, J., & Van Dyck, B. (2011). Reading space to ' address' spatial quality. *Spindus: Spatial Innovation Planning, Design and User Involvement*.

Moulaert, F., Van Dyck, B., Khan, A. Z., & Schreurs, J. (2013). Building a meta-framework to 'address' spatial quality. *International planning studies*, *18*(3-4), 389-409.

Nadin, M. (2018). Application of fuzzy logic in design of an aesthetics-based interactive architectural space.

Nady, A., Hassan, D. K., & Assem, A. (2023). A Proposed Framework for Automated Evaluation of Architectural Spatial Configurations Using Fuzzy Logic Approach. *JES. Journal of Engineering Sciences*, *51*(1), 19-48.

Naghibi Iravani, S., Karimimansoob, V., Arash Sohrabi, S., Gheitarani, N., & Dehghan, S. (2024). Applying Fuzzy Logic and Analysis Hierarchy Process (AHP) in the Design of Residential Spaces; Case of Study: Arak City, *13*(2), 144-160.

Nazari, A., & Torabi, M. R. (2022). Identification and Prioritization of Quality Indicators for Building Facade Design; Using a Fuzzy Approach. Journal of Iranian Architecture & Urbanism (JIAU), 13(2), 281-295.

Nordwall, U., & Olofsson, T. (2013). Architectural caring. Architectural qualities from a residential property perspective. *Architectural Engineering and Design Management*, *9*(1), 1-20.

Pakzad, J. (2002). Quality of space. Abadi, 2 (2), 100-110. [in Persian]

Punter, J., & Carmona, M. (1997). *The design dimension of planning: theory, content, and best practice for design policies*. Taylor & Francis.

Rapoport, A. (1970). The study of spatial quality. *Journal of Aesthetic Education*, *4*(4), 81-95.

Relph, E. (2016). The paradox of place and the evolution of placelessness. In *Place and placelessness revisited* (pp. 20-34). Routledge.

Rossi, P. H., Lipsey, M. W., & Freeman, H. E. (2003). *Evaluation: A systematic approach*. Sage publications.

Sanni-Anibire, M. O., & Hassanain, M. A. (2016). Quality assessment of student housing facilities through post-occupancy evaluation. *Architectural Engineering and Design Management*, *12*(5), 367-380.

Shao, Q.-G., Jiang, C.-C., Lo, H.-W., & Liou, J. J. H. (2023). Establishing a sustainable development assessment framework for a smart city using a hybrid Z-fuzzy-based decision-making approach. *Clean Technologies and Environmental Policy*, *25*(9), 3027-3044. https://doi.org/10.1007/s10098-023-02547-7

Simpson, J. A., Weiner, E. S., & Proffitt, M. (1993). *Oxford English dictionary: additions series* (Vol. 3). Oxford [England]: Clarendon Press; New York: Oxford University Press.

Sozen, M., & Tanyeli, U. (1994). Dictionary of Art Terms and Concepts. In: Remzi Publications, Istanbul.

Stringer, A., Dunne, J., & Boussabaine, H. (2012). Schools design quality: A user perspective. *Architectural Engineering and Design Management*, *8*(4), 257-272.

Thomson, D. S., Austin, S. A., Devine-Wright, H., & Mills, G. R. (2003). Managing value and quality in design. *Building Research & Information*, *31*(5), 334-345.

Tibbalds, F. (2012). *Making people-friendly towns: Improving the public environment in towns and cities*. Taylor & Francis.

Voordt, D. (2005). van der,(2005), Architecture in use: an introduction to the programming, design and evaluation of buildings. In: Amsterdam: Architectural Press.

Zadeh, L. A. (1965). Fuzzy sets. *Information and control*, *8*(3), 338-353.

Zemmouri, N., & Schiler, M. E. (2005). Application of fuzzy logic in interior daylight estimation. *Journal of Renewable Energies*, *8*(1), 55-62.

Zimmermann, H. J. (1996). *Fuzzy Set Theory - and Its Applications*. Springer Netherlands. https://books.google.com/books?id=vd9QAAAAMAAJ