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A Mamdani-Based Fuzzy Logic Model for Evaluating the Design Quality of Urban Squares

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Abstract

Urban squares are essential elements defining public interactions, cultural manifestations, and urban social characteristics. The spaces function as central meeting areas where citizens participate in civic duties, connect and serve to maintain urban design unity. The evaluation process of design quality proves challenging because it combines the personal interpretation of many complex variables, which standard assessment techniques struggle to measure. The researchers present a Mamdani-based fuzzy logic model that evaluates urban square design quality through eight core parameters: imageability, meaning, legibility, time, enclosure, dominance, diversity, and comfort. Fuzzy logic is an approximation system that converts evaluative statements based on linguistic expressions into numerical arrangements, which excel at interpreting multi-faceted urban design evaluations. The model underwent calibration through evaluations from 1,044 architecture professionals, planners, and landscape architects, and it was used to analyze 20 internationally recognized urban squares with various spatial designs across different cultural settings. The quantitative model demonstrated its accuracy by matching expert-aggregated scores when measured against predictions, with a precision of ±1.5% pin predicting outcomes. All examined variables confirmed that enclosure and comfort are the key factors influencing perceptions of design quality. The model provides practical applications for urban planners, decision-makers, and educators through its ability to create a standardized evaluation process for current and future urban interventions. The framework offers a distinctive approach that integrates design thinking-oriented methods with evaluative measures, rendering it practical for contemporary urban design practice.

Keywords:
Fuzzy logic, Public space, Urban square.

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INTRODUCTION

Cities incorporate urban squares as their most significant public areas, shaping community schedules and reflecting the social and cultural transformations or urban environments. Outdoor and multi-purpose settings with spatial anchors offer accommodation for various activities in addition to their use in gatherings, circulation, celebrations, and protests. Open spaces serve physical needs while satisfying symbolic expectations through their diverse functions and design features, which determine how people perceive and interact with them. Traditional urban square planning adheres to established principles, although the interweaving of space relationships tend to be irregular. Significant aspects exist in a network structure that transforms according to contextual and morphological variations and temporal changes.

Multiple publications present lists of the world's most successful urban squares while refraining from defining the specific characteristics that make them successful. Academic researchers have stepped in to address this knowledge gap through investigations aimed at discovering and assessing the important physical elements and perceptual characteristics of design excellence. Research identifies tactical and abstract design qualities through form, shape, enclosure, and perception-based factors such as imageability, meaning, and temporal sense. From antiquity to present day, various theorists, including Vitruvius (1960a, 1960b), Alberti (1986), Sitte (1986), and Zucker (1959a), have identified essential design criteria that define a well-designed square. Design quality analysis methods remain subjective, as these assessment models continually in response to prevailing cultural and temporal preferences. Different theorists employ the same concept of enclosure, interpreting it as a either a mathematical framework of rules or an intuitive signal.

Because defining essential design criteria remains a complex task, assessing design quality becomes inconsistent. Several urban settings exhibit such complexity, making it challenging to measure them using standard scoring systems. The inadequacy of these systems is evident in their inability to capture the characteristics that make up urban character during evaluation procedures. The evaluation method of public squares requires consideration of spatial arrangements, as well as an investigation of human reactions and cultural significance and time-based changes. A more flexible evaluation method becomes essential during this period of rapid urban development, as static and one-dimensional tools often fail to accommodate the dynamic and multi-layered nature of public squares.

Such conceptual confusion demonstrates that classical logic fails to grasp design quality because it typically involves a simple yes-or-no categorization. Research methods for urban design must adapt because this field includes multiple complexities, ambiguous elements, and subjective interpretation factors. Fuzzy logic is an alternative evaluation system that transforms verbal and ambiguous qualitative assessments into structured numerical outputs (Zadeh, 1965). Approximate reasoning

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forms the basis for fuzzy logic to operate effectively on systems that display non-linear substance and partial or indefinite data. Urban space is an appropriate subject for evaluation through fuzzy logic, as it combines physical experiences with emotional impressions resulting from both quantitative and qualitative attributes. Research shows that public environments succeed by combining structured physical elements with sensory elements, which help create psychological depth.

Such a model improves urban design practice by combining computer precision with human-based perception variability. The model is an essential connection that merges numerical processing with human observation by integrating specialist insights and place-specific factors during the evaluation process. As a system, fuzzy logic shows versatility in receiving diverse spatial interpretations associated with public spaces during contemporary globalization. The model demonstrates enhanced applicability across various sociopolitical and geographic settings, including historic European squares and current Middle Eastern and Asian public urban areas.

This research develops and implements a Mamdani-based fuzzy logic system to analyze the spatial quality of urban squares through physical variables and experiential parameters. A literature study by Alkan Bala and Üstüntaş (2014), Ferdous (2013), Mehta (2014), and Zawidzki (2016) enabled the identification of eight essential parameters: imageability, meaning, legibility, time, enclosure, dominance, diversity, and comfort for use in the model framework. The criteria represent fundamental assessment measures that specialists use in their evaluations of urban spaces, drawing both instrumental and holistic distinctions. According to Tibet (2024), the inclusion of perceptual sensitivity in computational models receives further evidence as the researcher demonstrates how fuzzy evaluation frameworks capture the symbolic and textural aspects of urban environments. MATLAB's Fuzzy Logic Toolbox was utilized to create the model through evaluation data obtained from 1,044 experts who reviewed 20 globally distinguished urban squares. Architects, urban designers, and landscape professionals rated the parameters using standardized visual materials and contextual descriptions during the evaluation process.

The model's basic assumption demonstrates how fundamental urban square design features affect users' perceptions, which can be evaluated using a fuzzy logic system analysis. Analysis was conducted using two evaluation methods: evaluating 179 expert professional surveys and a fuzzy logic protocol that employed identical parameters. The high correlation between expert perception and fuzzy modeling approaches demonstrates that expert intuition can be precisely predicted through the fuzzy modeling method while enhancing assessment scalability and reproducibility. This model accepts subjective spatial evaluation processes while generating evaluation data that specialists, designers, education professionals, and policymakers can understand.

The proposed evaluation method accepts both quantitative measurements and qualitative elements to provide an assessable solution for conventional evaluation systems. The system enables the creation of advanced assessment capabilities by recognizing quality gradations beyond binary success or failure results while establishing rankings through expert knowledge. The evaluation strategy shows particular value for cases where experiencing a sense of place, combined with perceptual enclosure, is equally essential as spatial maintenance and pedestrian activity. As a result, this established model serves as a tool for developing new urban squares and evaluating existing ones with the potential to guide academic training and urban policy development. This research employes a fuzzy logic model to resolve ambiguous meanings into quantifiable terms for structured decision-making processes.

The validation system for the spatial arrangement of an urban square provides a new multiscale evaluation based on expert panel agreement, utilizing concepts from fuzzy theory. This method serves as a crucial bridge, integrating the perception of design concepts with formal design attributes into a coherent system for evaluating key urban open spaces. The research combines theoretical frameworks with computer algorithms and empirical evidence collection to enhance current knowledge about measuring public domains in cities and their improvement methods. Researchers should capitalize on the developed foundation to build combination assessment systems that integrate AI systems with environmental analytics and public participant evaluations.

URBAN SQUARES AND RELATED DESIGN FEATURES IN THE LITERATURE

In literature, many theorists have defined and examined urban squares with different concepts and terms, revealing the characteristics that define the urban square across different interfaces. Although they are expressed differently in various languages, such as an agora, forum, plaza (Spanish), campo, piazza (Italian), or platz, when the design qualities are listed, a common language is complemented, binding and, connected (Özer & Ayten, 2005). In this common language, it is sometimes impossible to distinguish between concepts, a concept is often defined by incorporating many of them. In this context, it is difficult not to mention measurement when discussing form, measurement when discussing enclosure, order when discussing balance, and balance when discussing the layout. Definitions complement each other and establish a relationship network.

In the 1960s, Vitruvius defined the urban squares that he called the 'forum' through size, specific dimensions, and ratio relationships. Cullen (1971) defined them as "a place for everything" based on function, while Paul Zucker (1959a), who supported this statement, described the square as "a psychological parking place in public-on-public land. At another point, Lynch (1960), who referred to the urban square as the city's node, considered the square an element of the city to understand and recognize

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it and saw it as a strong image of the city. Alexander (1987) described this powerful image as a center for every city. He considers the square, one of the two elements described by Krier (1979), the city, as the first tool in using urban space, and refers to Jan Gehl (2011) as an open space surrounded by structures such as open space. Krier (1979) gave examples of the squares of the agora, mosque courtyards, and monastic courtyards of the city as an example of a city image. While creating the layout of urban space, the principles of implementation can be revealed by using principles such as order, form, symmetry, shape, and rhythm (Ching, 1979). A square feeling is created when these principles come together in the urban squares. This concept, mainly based on formal characteristics, is directly proportional to the feeling of siege/circumference. It is essential that there is an uninterrupted continuity in the surrounding structures or that the spaces are placed so that they do not disturb the feeling of closeness (Oktay, 2007; Sitte, 1986). It also relates to the scale. Width-height, width-length, and length-height are the most critical inputs in catching the scale, and this makes up the size of the urban square (Alkan Bala & Üstüntaş, 2014). Vitruvius (1960a) noted the necessity to consider the size of the urban square and the number of users.

The urban square design concepts were studied in two main topics in the literature. Studies in the first topic focus on the physical conditions of urban squares and try to formulate the main definitions and the essential components of an urban square. The second main study topic focuses on the perceptions of users about the urban square design (Alberti, 1986; Acar et. al., 2021; Alexander et al., 1977a; Alkan Bala & Üstüntaş, 2014; Altınçekiç & Kart, 2000a; Altay et. al, 2023; Ashihara, 1981; Bentley et al., 1985; Bostanci & Ocakçi, 2011; Çakmaklı, 1992; Çolakkadıoğlu &Büyüköztürk, 2024; Carmona et al., 2003; Carmona et al., 2010; Carmona, 2021; Carr et al., 1992; Ching, 1979; Cullen, 1971; Damayanti & Kossak, 2016; DETR/CABE, 2000; Ewing & Clemente, 2013c; Ferdous, 2013; Francis, 2003; French, 1978b; Gehl, 1987; Gibberd, 1959; Gold, 1980; Grammel et al., 1977; Jacobs & Appleyard, 1987; Köseoğlu & Erinsel Önder, 2010; Kostof, 1992; Kostof et al., 1992; Krier, 1979; Lang, 1987; Lefebvre & Régulier, 2004; Li et. al. 2024; Lovene et al., 2019; Lynch, 1960; Marcus & Francis, 1997; Mehta, 2008, 2014; Memlük, 2013; Moughtin, 2003; Nasar, 1998; Oktay, 2007; Önder & Aklanoğlu, 2002; PPS, 2000; Proshansky et al., 1983; Rapoport, 1977; Reis et al., 2003; Relph, 1976; Romano, 2004; Sepe, 2021; Sitte, 1986; Stamps, 2005; Stubben, 1924; Terzi et al., 2019; Trancik, 1986; Tunnard & Pushkarev, 1963a; Vitruvius, 1960b; Wang, 2002; Whyte, 1980; Zawidzki, 2016; Zucker, 1959a, 1959b). There are also lots of studies that consider both physical and perceptional dimensions of an urban square design. These studies research the ideal environmental conditions of an urban square primarily to identify and measure the design value of urban square design quantitatively and qualitatively (Figure 1). Numerous studies were examined, and essential and prioritized resources were presented in the literature review table (Table 1).

Figure 1. Frequency of urban square design features in the literature (Özyılmaz Küçükyağcı, 2020)

Table 1. Literature review for urban square design criteria (Özyılmaz Küçükyağcı, 2020)

DESIGN PARAMETERS

REFERENCES		Meaning	Upkeep	Style	Size	Vitality	Diversity	Encosure	Balance	Dominancy	Order	Disorder	Accessibility	Funciton	Form	Permeability	Widht/Height Raito	Visual Appeal	Visual Order	Safety	Hierarchy	İmageability	Character	Identity	Comfort	Centrality	Legibility	Proportion	Scale	Panoramic	Colour effect	Rhythm	Symmetry / Asymmetry	Continuity	Shape	Definiteness	Balance	Emphasis	Orientation	Time
1924	J. Stubben													X																										
1959	Paul Zucker			X	X			X		X	X			X	X		X									X														
1959	Frederick Gibberd				X						X			X	X													X	X											
1960	Vitruvius				X												X											X							X					
1960	Kevin Lynch	X			X						X		X									X		X			X					X			X				X	X
1963	Tunnard ve Pushkarev																					X		X																
1971	Gordon Cullen					X								X												X													X	
1976	Relph	X																																						
1977	Grammel et.al							X									X											X												
1977	Alexander et.al.			X	X			X	X								X								X															
1977	Michael Trieb							X									X																							
1977	Rapaport								X																															
1978	Jere Stuart French			X				X			X			X												X														
1979	Francis DK, Ching	X						X					X		X						X							X				X	X		X					
1979	Rob Krier			X											X												X								X					
1980	Whyte					X	X					X													X															
1980	Gold													X																										
1981	Ashihara				X																																			
1983	Proshansky	X																																						
1985	Bentley et.al.						X									X		X	X																					
1986	Camillo Sitte			X			X	X	X	X		X					X	X	X							X		X	X						X					
1986	Alberti							X						X	X		X																							
1986	Trancik				X	X				X								X				X				X	X									X			X	
1987	Jan Gehl				X		X				X			X				X				X																		
1987	Lang							X																																
1987	Jacobs et.al.	X					X						X	X										X			X													
1992	Carr et.al.	X											X	X											X															
1992	D. Çakmaklı			X		X	X	X			X			X				X																						
1992	Kostof			X							X				X														X											
1997	Marcus and Francis				X		X							X				X																		X				
1998	Jack Nasar		X																X											X						X		X		
2000	Altınçekiç ve Kart																																							X
2000	DETR/CABE						X	X					X										X				X							X						
2002	P. Wang													X								X																		
2002	PPS		X				X						X	X										X	X		X													
2002	S. Önder, F. Aklanoğlu			X							X		X	X	X							X						X												
2003	Cliff Moughtin					X	X	X						X	X			X																						
2003	Carmona et.	X					X	X		X			X		X									X			X									X	X		X	X
2003	Reis et.al.							X																	X															
2004	Lefebvre ve Régulier																															X								X
2004	Romano													X	X																									
2005	Stamps																																							
2007	Derya Oktay							X																																
2008	V.Mehta													X											X															
2010	Carmona et. al	X															X								X			X												X
2010	Köseoğlu ve Erisel Önder																										X													
2011	Bostancı ve Ocakçı						X		X		X			X	X				X												X						X			
2013	Ewing and Clementine	X						X																			X	X											X	
2013	Ferdous							X																																
2013	M.Memlük				X			X						X	X																									
2014	V. Mehta	X											X	X						X					X															X
2014	H. A. Bala & ÜStüntaş						X	X						X		X	X	X			X			X				X				X		X			X			
2016	Damayanti ve Kossak																																						X	
2016	M.Zawidski			X				X			X																													
2019	Lovene et.al							X									X											X												
2019	Terzi ve diğ.				X	X	X						X	X										X																
2021	Sepe					X							X												X															
2021	Carmona	X											X												X									X					X	
2021	Acar et.al.					X	X						X									X																		
2023	Altay et. al.						X	X	X		X		X	X	X	X				X							X		X		X				X				X	
2024	Li et. al.					X	X						X																											X
2024	Çolakkadıoğlu &Büyüköztürk		X					X					X	X						X			X	X																X

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The study aims to establish a clear framework, a necessity given the subject's complexity and the need to analyze multiple variables. The parameters under study were derived from a thorough literature analysis, ensuring their relevance and applicability to theoretical and practical fields. Istanbul's historical center has been a key area of analysis, drawing on Çınar and Çermikli's studies (2018,2019), which explored urban form interpretation to understand spatial memory and identity from a cognitive perspective. The researchers (Çınar & Çermikli, 2019) employed point density analysis in cognitive mapping to show how users' perceptions influence the spatial quality within historic urban configurations. As in this study, perceptual and physical parameters were used conjunction with this research (Çınar & Çermikli, 2019; Yıldız and Çağdaş, 2019).

In this context, urban squares, as public open spaces, underwent a detailed review, identifying imageability, meaning, legibility, time, enclosure, dominance, diversity, and comfort as the primary design attributes for the fuzzy logic model. Theoretical concepts related to square design evaluation are recurrent in academic literature, underscoring their status as fundamental elements (Yıldız and Çağdaş, 2020). Complete with sub-parameters, the model elucidates how each criterion contributes to the urban square experience within its conceptual framework. Since the subject focuses on urban squares as urban open spaces, the results of a detailed literature study indicate that eight basic parameters of squares have been identified for the proposed model. These have been chosen with consideration for the fact that numerous design features are included in many studies in the literature, emphasized and highlighted by theorists. The eight selected design attributes are; imageability, meaning, legibility, time, enclosure, dominance, diversity, and comfort. The sub-parameters of these parameters are also defined in the context of what they mean, what they cover, and their relationship with the urban square.

Imageability

Imageability, as proposed by Lynch (1960), is the quality that makes a place recognizable and memorable. This concept is heavily influenced by the legibility of spatial elements such as identity, structure, and meaning, as suggested by Damayanti & Kossak (2016). Their well-regulated design and distinct features often characterize cities with high imageability. Creating a strong urban image involves physical elements that attract attention and evoke emotions. Notably, landmarks and architectural arrangements play a significant role in this process, as Ewing and Clemente (2013b) discussed. Notable urban squares such as Piazza San Marco, serve as city focal points and symbolic references, as highlighted by Önder & Aklanoğlu (2002).

Meaning

The meaning of a space is defined by personal experiences and historical events (Relph, 1976; Lynch, 1960). It is a concept that is closely related to perception, identity, and structure (Proshansky et al., 1983), sparking our curiosity. The meaningfulness of a place is enhanced by its historical and political significance, which influences how spaces are perceived and utilized (Mehta, 2014; Lang & Marshall, 2016).

Legibility

Legibility, the ease of navigating and understanding urban space, is influenced not only by sensory experiences but also by spatial properties (Bentley et al., 1985; DETR/CABE, 2000). This emphasis on spatial properties provides the audience with a sense of being informed and knowledgeable.

High legibility, which depends on pedestrian movement and reference points, is significantly impacted by building scale, density, and orientation. These factors play a crucial role in user satisfaction and spatial understanding (Krier, 1979; Bostanci & Ocakçi, 2011; Samavati & Ranjbar, 2017), making the audience aware of their practical implications.

Time

Time is closely related to the meaning of space and its historical and political context (Carmona et al., 2010; Mehta, 2014). It is experienced through rhythmic or progressive changes and affects the continuity and development of urban spaces (Lynch, 1972; Altınçekiç & Kart, 2000). Temporal cycles, cultural heritage, and daily life rhythms influence the city's formation and architectural space (Lefebvre & Régulier, 2004).

Enclosure

The enclosure is a crucial aspect of urban spaces, defining the visual aspect of the urban space. It is defined by vertical and horizontal elements that limit the user's field of view. The enclosure's corner points and edges are crucial in defining the place (Moughtin, 2003). Jan Gehl created the behavior map in Piazza del Popolo in 1965, noting that people prefer to sit and rest on the edges of the square, the most frequently used area (Gehl & Svarre, 2013). The degree of enclosure is determined by the character of the surrounding elements, which are influenced by the height and width of the space. The degree of enclosure, dependent on the ratio between the surrounding buildings' height and the urban square's width, creates the feeling of enclosure (Dee, 2004; Gehl, 1968; Lovene et al., 2019). The ratio should decrease or increase linearly to avoid losing the sense of an urban square, while a higher ratio can cause the feeling of being surrounded to disappear entirely. The quality of the elements, the level of the enclosure, and the order of the surrounding aspects affect the spatial quality of the urban square (Alkan Bala & Üstünbaş, 2014; Altay

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et. al, 2023; Çakmaklı, 1992; Çolakoğlu and Büyüköztürk, 2024; Sitte, 1889)

Dominance

Urban squares have evolved in response to religious beliefs and political influence, with administrative or religious buildings often being the most dominant structures. These structures host various activities and events, revealing the power of administration and defining unique spatial contexts (Wolfrum, 2014). The "dominated square" type in Zucker's (1959b) urban square identification states that the square is shaped around a center, with all other structural elements associated with this structure. Dominance in space refers to the character of one or more structures or physical elements that contrasts with the surroundings and is situated at a prominent point, thereby ensuring readability and orientation (Carmona et al., 2010). Features such as size, design, location, quality, and function affect dominance and contribute to the identity and image of the space (Trancik, 1986). The dominance effect created by buildings in squares encompasses the contrast between the building's size and that of the surrounding buildings, which interferes with perception of shape, color, texture, form, and size (Lynch, 1960). (Figure 2)

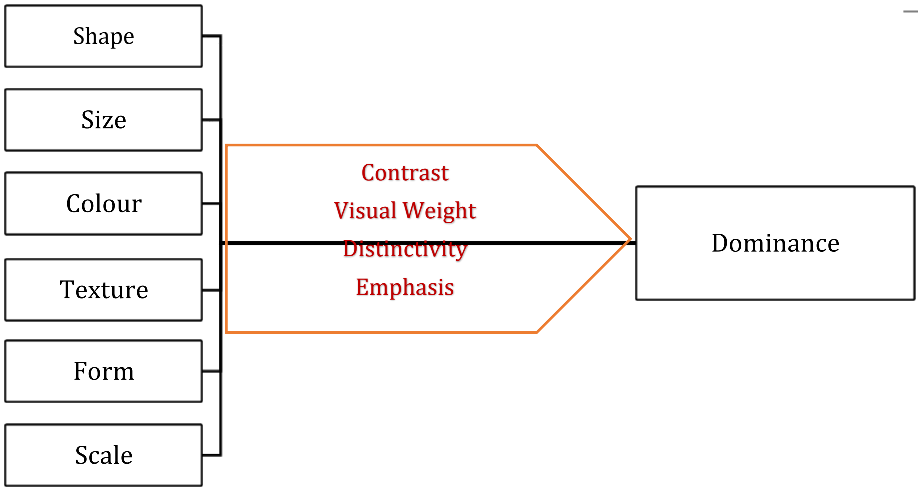

Figure 2. The qualities of principles that create dominance (Özyılmaz Küçükyağcı, 2020)

Diversity

Rapoport (1977) emphasizes the importance of 'noticeable differences' in place design, as they create diversity in urban spaces. This study focuses on the diversity in urban squares through physical texture and activities. Camillo Sitte (1986) emphasizes the importance of building blocks, street widths, and connections to ensure diversity in spatial design. Diversity can be achieved through various factors, such as contour effects, vertical and horizontal elements, forms, facade colors, building functions, elevations, and activities (Sitte, 1986). The diversity in squares can also be achieved through increased variety and density of activities, which increase livability and visual appeal. These also provide social benefits, such as reducing loneliness and providing recreational opportunities (Acar et. al, 2021; Altay et.al. 2023; Bostanci & Ocakçi, 2009; Çakmaklı, 1992; Gehl, 2011; Li et. al. 2024; Marcus & Francis, 1997; Moughtin, 2003; Tönük & Barkul, 1999).

Comfort

Comfort in public spaces is a fundamental user need, allowing users to enjoy their time outside without physical or mental concerns (Carmona et al., 2010). It depends on various parameters, including safety, security, and spatial arrangements (Carr et al., 1992). Urban squares, with facades and entrances, provide a sense of security, while windows in houses, cafes, and shops increase social control (Alfonzo, 2005; Mehta, 2008; Reis et al., 2003). Safety in urban equipment is closely linked to people's confidence, while optimum climate conditions and suitable spatial arrangements increase comfort. Protected areas from sun and rain increase space use, and quality spaces contribute to climatical comfort.

Thus, this study aims to evaluate the design value of urban squares with different physical and perceptional conditions. Regarding spatial design's fuzzy and complex nature, fuzzy logic modeling and fuzzy sets theory are integrated into the research. This study focuses on urban square design, examining factors such as imageability, meaning, legibility, time, enclosure, dominance, diversity, comfort, and related sub-parameters. (Table 2.)

Table 2. Design parameters and sub-parameters of urban square (Özyılmaz Küçükyağcı, 2020)

IMAGEABILITY	The presence of image buildings in the urban square. Attractive color effect The fact that the city is located at the focal points (city symbol) Remarkable land uses Presence of steering axles Important reference points (fountain / sculpture) The original value of the square (Form-Material-Construction Technique)
MEANING	Presence of historic preservation structures Being a political symbol Elements with meaning/value/image/story in the square Important historical events in the square
LEGIBILITY	The existence of symbol structures Defined areas in the square Surrounded and continuous texture Having the defined geometric form of the square Oriented tracks and axles Symmetry effect
TIME	The existence of the time sequence of the buildings Having traces of historical periods of the square Periods of important events and attractions in the urban square (during the year)
ENCLOSURE	Having a closed shape The presence of image buildings in the square Attractive color effect Width/length ratio (plan level)
DOMINANCE	The dominant structure / structures in the square Effect of dominant structure/structures in the surrounding texture of the square The effect of the dominant structure/structures in the focus/center of the square

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DIVERSITY	Movements in line (Contour effect) Variety of vertical items Variety of horizontal items Structures in different forms (geometric/organic) Facade colors Variety of functions on the buildings Variety of functions in the entrance floors Different floor levels Annual activity/ event variety
COMFORT	Percentage of non-deaf fronts The proportion of buildings facing the entrance Percentage of abandoned / vacant / abandoned buildings The proportion of good quality structures Ground slope Illuminated places Sitting places on the square Precautionary areas against climatic conditions

A FUZZY MODEL FOR EVALUATION OF URBAN SQUARE DESIGN

The urban square design is often evaluated using various research methods based on classic theory, providing a crisp, deterministic, and precise foundation. However, to accommodate the subjective nature of design concepts, fuzzy interpretations are incorporated for different levels of spatial designs. Despite these efforts, achieving clarity in design concepts remains challenging, as spatial design is intuitive, and the interpretation of design concepts is subjective. Consequently, identifying a definitive truth for every design concept is problematic. So fuzzy logic is closer to the real world as an approach considering multivariate and intermediate values (Baykal & Beyan, 2004). In binary logic, a subject is black or white between black and white sets, while in fuzzy logic, it takes a value in a range that transitions from black to white; it helps to take a more accurate result in decision-making. Additionally, it has advantages such as facilitating the conversion of linguistic data to numerical data, enabling flexible modeling of multivariate concepts, and simplifying the analysis of subjects with ambiguous and unclear information.

This approach is widely used in various disciplines, particıularly in engineering. Although there are studies in the literature that address urban area issues using a fuzzy logic approach, they are limited in number (Özyılmaz Küçükyağcı, 2019). The results of the studies on the applications of the FLM in urban areas, including how it was handled, the findings reached, and the contribution of the approach to the studies were evaluated. According to this, since a fuzzy model can be established with the multivariate structure of the concept of design, which is the subject of the study, it has been included in the research.

The research integrates fuzzy logic and fuzzy sets theory instead of classical logic due to the variability in concept definitions. It explores how urban squares reflect design characteristics based on imageability, meaning, enclosure, dominance, time, legibility, comfort, and diversity. A parameter sequence was developed to explain and evaluate the scope of the sub-parameters.

In the context of the structure and characteristics of the spatial design concept, the fuzzy logic approach, which is suitable for evaluating this concept, has been used. The established research model was integrated into the fuzzy logic model, one of the methods compatible with working with multivariate concepts. The reason for choosing this method is that it enables the flexible modeling of design features, incorpating both verbal and linguistic elements, as well as physical and quantitative values. While the model was being built, it was seen that it was necessary to be sensitive in measuring all the attributes, especially meaning and time. To measure the value of a design attribute of the square on a scale ranging from 1 to 100, it has been observed that using a system with high permeability between clusters, rather than clusters with a clear range, helps to receive and process data more accurately.

Research methodology for evaluating design parameters of urban squares

To assess the model designed to measure the design value of urban squares, the study examined twenty squares from various countries. These squares, frequently mentioned in literature and widely recognizable as successful or unsuccessful, were chosen for their originality and diverse morphological features.

The study develops an integrated method for analyzing twenty urban squares. To reach valid results and thoroughly present the design value of urban squares, the study starts with a literature review of the design parameters of urban squares and the methods used to evaluate the design quality of open spaces. The steps of the methodology are:

1) An in-depth literature review - determination of relevant parameters of urban squares

2) A fuzzy logic modeling through parameters

3) Testing the fuzzy logic model on selected urban squares

The MATLAB Fuzzy Toolbox was used in conjunction with Simulink software to implement and set up the model. The model design process for fuzzy logic utilized MATLAB Fuzzy Logic Toolbox in conjunction with Simulink as its execution platform. The toolbox provides a visual interface that simplifies the design of fuzzy inference systems through step-by-step processes for defining linguistic variables and constructing membership functions and rule sets. This system functions with Simulink, which allows users to conduct real-time simulations to test the adjustability of their model structure. This system provides adaptable conditions for converting professional expertise into machine-based algorithms. The model employs Mamdani-type fuzzy inference systems, a popular approach for decision-making applications that compute outputs through combined human-based reasoning patterns. Mamdani systems excel in problems with imprecise information because they allow both linguistic variable handling and controlled state shifting between input and output data. The system utilizes fuzzy values to characterize urban design qualities like "comfort" and "legibility" through this process. As a result, it did not need strict binary classification. The eight input variables were represented using triangular membership functions that define

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linear geographically shaped assignments for measuring degrees of membership in fuzzy sets. These were chosen for their computational efficiency and ease of interpretation. The reference to "triple membership functions" denotes the three linguistic categories assigned to each input: low, medium, and high. These categories allowed the model to capture subtle gradations in expert judgment. On the output side, the design value was expressed through five fuzzy categories ranging from "very low" to "very high," providing a broader resolution in the evaluation scale. The fuzzy rule base comprised 6,561 rules derived from all possible combinations of the eight input variables. This combinatorial structure ensured that the model accounted for the full design parameter interactions. The FLM includes blurring, rule-based creation, refinement, and extraction. The main elements of a fuzzy model are input-output sets and fuzzy 'if–then' rules. The study employed eight inputs and one output and established 6561 rules for the system. In this study, the input variables of the fuzzy model are 'imageability, meaning, legibility, time, enclosure, dominance, diversity, comfort', while the output variable is design quality (Figure 3).

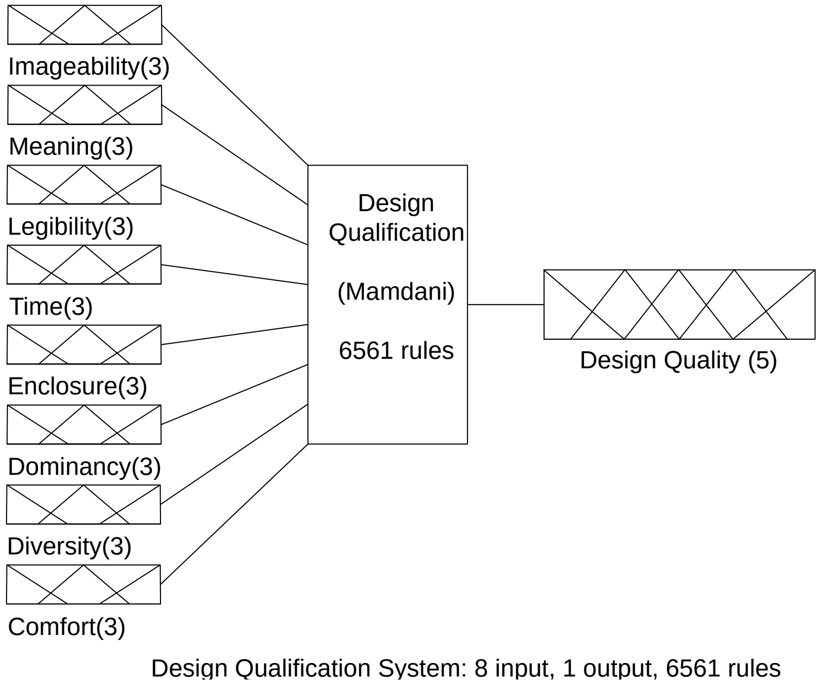

Figure 3. A Mamdani-type fuzzy model for design qualification (Özyılmaz Küçükyağcı, 2020)

A triple-membership function (mf) for eight inputs and the five-member function (mf) for one output has been created. The triangular membership function was used as it is one of the most common membership functions used in rule-based fuzzy modeling. Being easier to interpret and analyze, the Mamdani fuzzy inference system was the model of choice for design qualification purposes. The parameters of the membership functions represent input and output variables in the constructed fuzzy design qualification model. While the input variables consist of three fuzzy sets with low, average, and high values, the output variables comprise five fuzzy sets: "very low, low, average, high, and very high."

The final stage of constructing a fuzzy model is to define fuzzy if-then rules. The 6561 if-then rules were generated and introduced to the fuzzy model. While creating the rule base, a 6561-rule base is created by entering the values that eight parameters will take for each condition. Thus, a model was established to measure the design quality of the urban square, utilizing eight parameters similar to those of an expert designer.

The architecture of the fuzzy logic model was deliberately structured using eight input variables, each represented through three linguistic categories—low, medium, and high—resulting in a total of 6,561 fuzzy inference rules (3^8 combinations). This expansive rule base was necessary to capture the full complexity of interrelationships among the design parameters. Each rule was constructed to reflect a plausible, logical interpretation of how combinations of qualities (e.g., high enclosure with low legibility) influences overall design value. The decision to employ three membership functions per input parameter was guided by two key criteria: interpretability and computational efficiency. A tripartite structure allowed nuanced differentiation while maintaining readability for human experts who validated the rule sets. On the output side, five membership categories were used to reflect more granularity in the model's final design quality index. This provided a broader scale to distinguish spaces with marginal or exceptional performance, which would not have been adequately represented with fewer output classes. Rule validation was conducted through iterative expert feedback sessions and simulation testing, ensuring that each rule produced logically consistent and contextually appropriate outputs across a diverse sample of urban squares.

Testing the model

To test the model an empirical study was conducted to test the proposed model through selected urban squares that have different qualifications from different countries (Italy (6), Germany (1), France (2), Iran (1), Spain (1), Sweden (1), Belgium (1), from the Czech Republic (1), the UK (1), Portugal (1), United States (1) and Turkey (3)).

During the implementation phase, surveys were conducted with 179 experts from different occupational groups, including architects, landscape architects, and city planners, for twenty (20) urban squares. A balanced distribution was provided for the survey study, as a ratio of more than 30% from each discipline was reached in the distribution of occupations. Sixty-three architects, 62 urban planners, and 54 landscape architects responded to the survey; they are mostly (% 85) academic. The eight criteria determined in the questionnaire were scored using the information from the selected urban squares.

The experts answered the questionnaire by selecting at least five known urban squares. The data obtained from each expert were analyzed

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using fuzzy logic with MATLAB software, and the total design value of each square was determined.

In the survey, participants chose at least five squares, scored between 1 and 100 points for each criterion, and provided a total score within the design value of each square. A total of 1059 survey results were collected for 20 squares. The collected 1059 data was used to check whether the fuzzy logic system works. It was also tested whether the system gave results like the experts, and the findings were compared and evaluated. To support methodological transparency and replicability, the expert questionnaire was structured to collect evaluations across eight key urban design criteria: imageability, meaning, legibility, time, enclosure, dominance, diversity, and comfort. Each criterion was rated on a 100-point scale, and participants were provided with consistent visual and textual references for each urban square to ensure uniform interpretation. The format allowed for numerical scoring and optional qualitative input, though only the quantitative data were used to calibrate and validate the fuzzy logic model. The instrument's design followed established perceptual evaluation practices, allowing for consistent and scalable application across diverse spatial contexts.

Considering the number of surveys, it is evident that Piazza San Marco is the square that experts evaluate the most, while Naqsh-e Jahan Square is the least answered. Based on the data in the context of the survey numbers, it is possible to assess the recognition and awareness of the urban squares. However, 4 out of 20 squares have stayed under 30: Piazza Della Cisterna, Hötorget Square, Place Vendome, and Naqsh-e Jahan Square. According to this study, urban squares with fewer than 30 survey results can have low recognition although it has good qualifications. (Figure 4).

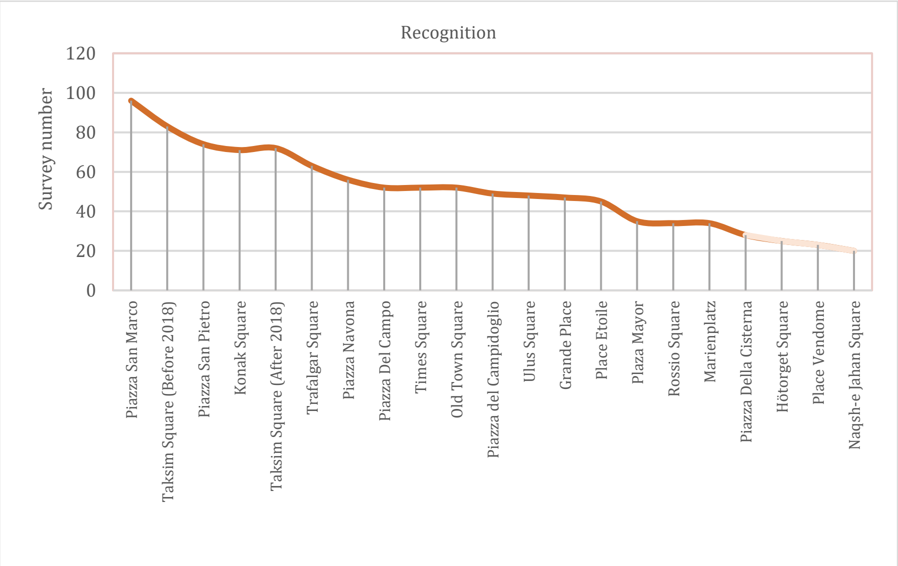

Figure 4. Recognition level of urban squares according to survey data (Özyılmaz Küçükyağcı, 2020)

General findings of the research

The findings of twenty case studies are as follows. First, this study shows a clear relationship between the selected criteria and urban square design value. According to the result of the correlation analysis, the relationship between each variable and the design is positive and significant. Enclosure and comfort parameters have the highest relationship with design value (Table 3).

Table 3. Correlation between design value and design parameters (Özyılmaz Küçükyağcı, 2020)

Design parameters	Correlation	Design Value
Comfort	0,82742192	
Enclosure	0,81021671	
Legibility	0,78712576	*High Level Relationship*
Imageability	0,77836856	
Dominance	0,73186045	
Time	0,70474427	
Meaning	0,60603522	*Moderate Level Relationship*
Diversity	0,57989401	

According to the findings, the relationships are constructed correctly in the model. In the survey results, while the famous, well-known urban squares, shown as exemplary in terms of successful design, received high scores for each criterion, squares with inadequate qualifications received low scores from experts. A proportional result was observed when the study results were examined according to each design criteria of the urban squares. When a general evaluation is made of the results obtained, it is seen that the results of the fuzzy logic model overlap with a slight difference when the scores given by the experts are compared. The difference between the fuzzy logic results and the total design value varies between -18.9% and 3.12%, while the difference between the arithmetic mean values is between -3.8% and 0%. The difference between the arithmetic means values and fuzzy logic results is less, with an average of 1.49%. In this context, the model works like artificial intelligence by creating similar results to experts with a slight deviation in decision-making (Table 4).

Table 4. Comparison of fuzzy logic results with survey data (Özyılmaz Küçükyağcı, 2020)

Urban Squares	Total Design Value	Fuzzy Logic Model Results	Standard Deviation		Arithmetic Average Values	Fuzzy Logic Model Results	Standard Deviation	
Piazza del Campidoglio	0,882	0,867	1,7%		0,857	0,867	-1,2%	
Piazza San Marco	0,892	0,864	3,2%		0,865	0,864	0,1%	
Piazza San Pietro	0,871	0,860	1,3%		0,861	0,860	0,1%	
Old Town Square	0,867	0,858	1,0%	**-2,4%**	0,851	0,858	-0,9%	**-1,49%**
Piazza Del Campo	0,873	0,857	1,9%		0,846	0,857	-1,3%	
Piazza Navona	0,874	0,856	2,1%		0,847	0,856	-1,0%	
Marienplatz	0,811	0,840	-3,4%		0,814	0,840	-3,1%	

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Piazza Della Cisterna	0,856	0,834	2,7%		0,826	0,834	-0,9%	
Grand Place	0,833	0,831	0,2%		0,825	0,831	-0,8%	
Rossio Square	0,840	0,831	1,1%		0,819	0,831	-1,5%	
Place Vendom	0,827	0,827	-0,1%		0,818	0,827	-1,1%	
Trafalgar Square	0,806	0,814	-1,0%		0,791	0,814	-2,9%	
Plaza Mayor	0,801	0,807	-0,7%		0,807	0,807	0,0%	
Naqsh-e Jahan Square	0,778	0,794	-2,1%		0,786	0,794	-1,0%	
Place Etoile	0,732	0,778	-5,9%		0,773	0,778	-0,7%	
times Square	0,708	0,739	-4,3%		0,729	0,739	-1,4%	
Hötorget Square	0,667	0,700	-4,7%		0,675	0,700	-3,5%	
Konak Square	0,663	0,688	-3,7%		0,663	0,688	-3,8%	
Nation Square	0,587	0,655	-10,4%		0,640	0,655	-2,4%	
Taksim Square (before 2018)	0,575	0,636	-9,6%		0,619	0,636	-2,7%	
Taksim Square (after 2018)	0,397	0,490	-18,9%		0,483	0,490	-1,5%	

The fuzzy logic model generated outputs that closely aligned with the expert evaluations across the 20 selected urban squares. The comparison revealed a mean absolute error of ±1.5%, confirming the model's reliability in translating qualitative spatial judgments into consistent quantitative scores. This alignment was powerful in squares that exhibited apparent morphological coherence and active edge conditions, supporting the long-standing emphasis in urban design literature on enclosure and comfort as key determinants of spatial quality. Notably, these two parameters consistently registered the highest correlation with the model's overall design quality index, reinforcing observations made by Gehl (2011) regarding the importance of framed space and human-scaled environments in fostering vibrant public life. Principal component analysis further grouped the evaluated squares into three broad performance categories. High-scoring examples such as Trafalgar Square and Piazza del Campo demonstrated strong enclosure, clear spatial legibility, and diverse functional layers. At the same time, mid-range cases, such as Place de la République, scored well in comfort and imageability but exhibited weaker coherence in terms of meaning and temporal dimensions. Lower-scoring squares, such as Hassan II Square in Casablanca, tended to lack perceptual continuity or spatial dominance, aligning with Lynch's (1960) theory on the importance of identity and readability in public environments. While some overlaps between variables were expected due to the interdependent nature of spatial experience, the fuzzy logic model preserved distinct weighting across all eight parameters. The resulting evaluation scores offered a nuanced yet statistically stable distribution, with no single parameter overly skewing the outcome. These findings confirm that the model can accommodate

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subtle variations in square typologies while preserving conceptual clarity and internal consistency.

Like the average of the experts' total design scores, the fuzzy logic model also gave results in a linear line. In the fuzzy system, urban squares with low values give a low overall result, and when the high values are entered, the total is close to 1 or higher in the fuzzy logic model. Since the average of the result for each square is similar to the result of the fuzzy logic model, it can be said that the rule base was appropriately written in the fuzzy logic model. It is observed that this proposed model evaluates the design of the square using design criteria similar to those of an expert. The main distinguishing feature of this fuzzy modeling is that the intermediate values can be modeled in different clusters simultaneously, and the clusters can vary in different qualities according to the theory. The model, designed with eight criteria, proved successful in evaluating design success; however, it provided a limited framework for an integrated design value.

When the rankings of the squares are determined based on the three results obtained, they are ranked similarly according to the design value of the squares, although there is a slight difference between the rankings (Figure 5.) Although the breaks are noticeable in Marienplatz and Trafalgar Square, the squares are ranked similarly on each curve when a general evaluation is made.

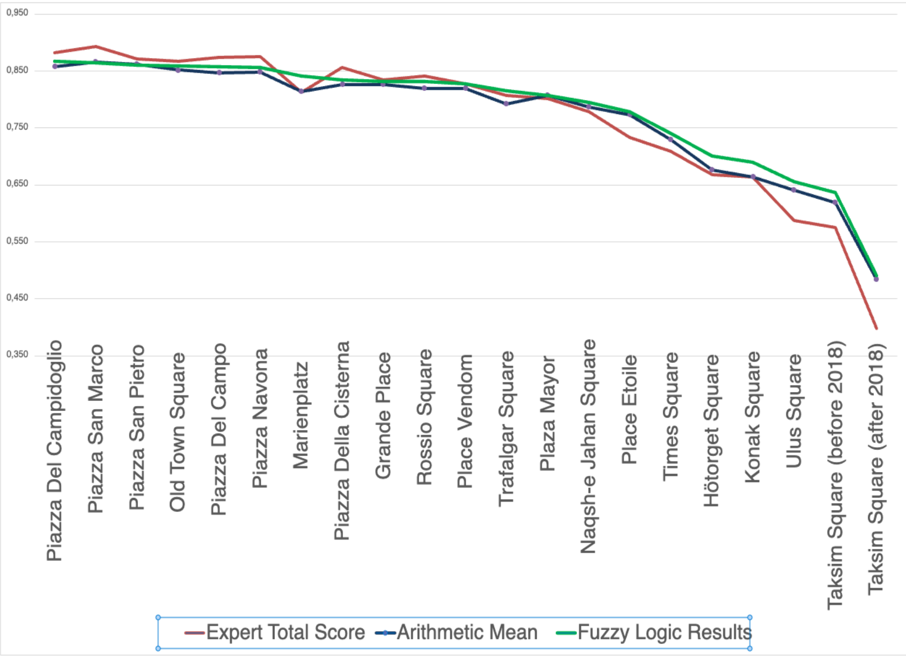

Figure 5. Comparison chart of the results (Özyılmaz Küçükyağcı, 2020)

The design success ranking of the squares, evaluated based on the results of 1049 questionnaires for 20 urban squares, completes the empirical aspect of the model. In the examples, the urban squares, built in the Middle Ages, possessed the characteristics of a typical urban square design and came to mind first, ranking at the top. Although there are significant differences between squares such as 'Piazza San Marco, Piazza San Pietro, and Piazza del Campo,' each is the most successful in the

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world. The fuzzy model results determined the nuance differences between the characters of these squares. In particular, an immeasurable value such as 'meaning' has been integrated into the model and evaluated by considering the range of values given by the expert instead of 'meaningful or not meaningful.' With the three results obtained, the design values of the urban squares were ranked in order from the highest to the lowest value. In the rankings, in the group with the highest design value, Piazza San Marco, Piazza Del Campidoglio, Piazza Navona, Piazza Del Campo, Piazza San Pietro, and Old Town Square make up the top six. According to the three rankings, although the urban squares' order changes, the squares' design level is the same. The other group comprises Piazza Della Cisterna, Rossio Square, Grande Place, Place Vendome, Marienplatz, Trafalgar Square, and Plaza Mayor. These squares are located between the 7th and 13th rows between 20 urban squares. The last group consists of Naqsh-e Jahan Square, Place Etoile, Times Square, Hötorget Square, Konak Square, Ulus Square, and two situations of Taksim Square. The last eight rows of the ranking (between 14 and 21) have the same order according to all three results as in the other groups. When these groups are evaluated within themselves, the urban squares within each group exhibit many characteristics, and these evaluations confirm that the survey results and the model yield accurate results.

Table 5. Design value rankings of the urban square (Özyılmaz Küçükyağcı, 2020)

	Ranking by Total Design Values	Ranking by Arithmetic Mean Values	Ranking by Fuzzy Logic Results
I. Group	Piazza San Marco	Piazza San Marco	Piazza Del Campidoglio
	Piazza Del Campidoglio	Piazza San Pietro	Piazza San Marco
	Piazza Navona	Piazza Del Campidoglio	Piazza San Pietro
	Piazza Del Campo	Old Town Square	Old Town Square
	Piazza San Pietro	Piazza Navona	Piazza Del Campo
	Old Town Square	Piazza Del Campo	Piazza Navona
II. Group	Piazza Della Cisterna	Piazza Della Cisterna	Marienplatz
	Rossio Square	Grande Place	Piazza Della Cisterna
	Grande Place	Rossio Square	Grande Place
	Place Vendome	Place Vendome	Rossio Square
	Marienplatz	Marienplatz	Place Vendome
	Trafalgar Square	Plaza Mayor	Trafalgar Square
	Plaza Mayor	Trafalgar Square	Plaza Mayor
III. Group	Naqsh-e Jahan Square	Naqsh-e Jahan Square	Naqsh-e Jahan Square
	Place Etoile	Place Etoile	Place Etoile
	Times Square	Times Square	Times Square
	Hötorget Square	Hötorget Square	Hötorget Square
	Konak Square	Konak Square	Konak Square
	Ulus Square	Ulus Square	Ulus Square
	Taksim Square(Before 2018)	Taksim Square(Before 2018)	Taksim Square(Before 2018)
	Taksim Square (After 2018)	Taksim Square (After 2018)	Taksim Square (After 2018)

Unlike the order made in three groups, for twenty-one squares, fifteen are clustered as one group and the other six as a separate group. The squares with low design values were separated from the others in these groups and gathered in the same group (Table 5).

DISCUSSION

While designing a place, a designer intuitively synthesizes knowledge, experience, and skill on paper. The integration of the designer's interpretation with different principles creates distinct values. Each element's relationship, position, and effect influence the design's success and user value. Achieving appropriate space design for all urban functions is essential. Urban-related subjects are often specific and complex, making fuzzy logic a valuable approach. For example, regulating city traffic involves many factors which fuzzy logic can effectively address.

The success of a well-designed place depends on various design parameters, which are hard to measure objectively. Typically, users and experts assess it. While classical logic employs pair-wise comparison, fuzzy logic offers a more plausible and rational evaluation method.

Fuzzy logic allows truth values between 0 and 1, handling partial truths, unlike Boolean logic, which uses binary values of 0 or 1. It reflects how people make decisions based on imprecise, non-numerical information. Fuzzy models represent and manage vagueness and uncertainty, recognizing, interpreting, and using imprecise data. (Baykal & Beyan, 2004; Ödük, 2019).

Fuzzy logic has been applied to many fields, from control theory to artificial intelligence. It has several strengths, such as its ability to handle imprecise data and model complex systems. However, it also has some weaknesses, such as its inability to handle uncertainty in a systematic (Ödük, 2019). In addition, since "humans" determine the membership functions and rule bases used in fuzzy logic, these functions and rule bases must be selected correctly. Otherwise, incorrect results may be obtained (Özdemir & Kalınkara, 2020; Zadeh, 1965). One of the disadvantages of fuzzy logic systems is the difficulty of designing the model. There is no specific method for selecting membership functions used in fuzzy logic; the most suitable function is typically found through trial and error. This prolongs the study process. This study aims to discuss "design," an intuitive concept with its parameters, using the strengths of the fuzzy logic method.

In this context, this study proposes a fuzzy logic-based model that operates similarly to the reasoning of architects, landscape architects, city planners, and city designers, enabling them to evaluate design through logical analysis. This model focuses on urban squares and aims to draw a frame on the scale of urban squares using the FLM and to measure design success using urban design parameters as an expert.

With the determined criteria, the design value of urban squares has been evaluated using the advantages and flexibility of the fuzzy logic method. The eight input parameters—imageability, meaning, legibility, time, enclosure, dominance, diversity, and comfort—can be modified, expanded, or reduced depending on the availability of data and the focus of the assessment. While each parameter was weighted equally in this study, the model allows for customization by assigning different weights

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based on priority, thereby generating alternative outcomes under varied design assumptions.

Although the present model is built around these eight criteria, it remains adaptable to include additional or more context-specific design features such as walkability, spatial continuity, or environmental comfort. Likewise, output variables can be adjusted to reflect different interpretations of success, enabling the model to simulate multiple outcomes using alternate rule structures. The modular design structure enables objective and uniform outcomes from the model irrespective of domain specialist input. Urban perception evaluation becomes possible through this systematic approach for quantifying complex architectural traits in urban settings.

The fuzzy logic model developed in this research demonstrates extensive practical application potential across various urban design settings due to its methodological and theoretical framework. Municipal governments and public agencies can implement the model as a standardized evaluation system for assessing both present and new proposed urban squares. The model's ability to convert intricate qualitative observations into measurable results enables planners and decision-makers to support their interventions and funding decisions while establishing performance targets for public space initiatives. Especially in contexts where public realm investments must demonstrate measurable social impact, the model is a diagnostic tool that complements more conventional regulatory and aesthetic criteria.

In educational settings, the model can be used as a pedagogical framework in architecture and planning studios to introduce students to systems thinking and decision-support tools. By engaging with fuzzy logic principles, design learners can better understand how qualitative judgments—often central to early-stage concept development—can be formalized and interrogated through structured reasoning. The model also supports the comparative evaluation of design proposals in academic juries, enabling a more consistent and objective assessment process without eliminating the value of critical discourse.

From a policy perspective, the model's ability to reveal which spatial attributes are most closely linked to perceived quality could inform the development of context-sensitive design guidelines and quality assurance protocols. As cities worldwide adopt increasingly data-informed approaches to urban governance, integrating fuzzy logic into evaluation workflows could help close the gap between abstract design principles and actionable policy tools. The model's adaptability to different cultural and morphological contexts makes it especially suitable for application in international design competitions, post-occupancy evaluations, or pilot projects focused on inclusive and climate-resilient public spaces.

CONCLUSION

The research presented a Mamdani-based fuzzy logic model to develop a systematic approach for assessing urban square design quality, combining spatial characteristics and perceptual elements. The quantification process utilized eight fundamental design attributes, including imageability, legibility, dominancy, enclosure meaning, time, diversity, and comfort, to model a measurable index that connects human perception with computational evaluation. The methodological reliability of the system resulted in an accuracy of ±1.5%, in line with the assessment of experts.

The model used fuzzy logic to represent intangible qualities that typically prove challenging to measure by traditional evaluation methods. The model incorporated two parameters that resist binary measurement through structured linguistic variables because they manifest culturally or symbolically and experientially. Such a system established a framework that detects concrete, measurable criteria and delicate perception points in evaluations. The implemented framework presents a structure representing complex urban areas while enabling design judgment to function inconsistently in adaptable ways.

The research results validated previous theoretical propositions that suggest that enclosure and comfort are the core elements for assessing urban space quality. The model highlights these factors as core priorities because Gehl (1987), Carmona (2021), and other theorists confirm that human-scale definitions and sensory openness lead to successful public spaces. The model received validation based on expert judgments because it generated outcomes that matched their assessments, thus demonstrating that fuzzy systems maintain both technical foundations and design interpretation quality.

The model provides relevant implications for practical use beyond its theoretical value. Staff from municipalities and educational institutions can use this model to gather evidence for funding public spaces and implement computational thinking into their urban design training programs. Due to its capability to define parameters and rules, the system can be adjusted to meet different cultural requirements or design purposes. The model demonstrates strong adaptability, making it a beneficial tool for academic uses and real-world design application requirements.

Future research on this framework can include expansion into areas such as integrating environmental data from GIS systems, improving membership functions by collecting user feedback, and extending model applications to parks, waterfronts, and linear corridors. The interpretable structure of this model enables its combination with agent-based simulations or neural networks, thereby enhancing its predictive strength and facilitating better decentralized decision-making.

The proposed fuzzy logic model serves academic research by advancing methodological discussions and operational practices through a solid theory-based public space quality evaluation system featuring

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scale and reliability. This method matches expert performance by eliminating dependence on expert participation, which positions it as an assessment tool and educational resource for building perception-aware, and more successful spaces.

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Resume

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