Modelıng of Heterogeneous Server Systems of a Smart Cıty in an Uncertaın Envıronment

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Abstract: The research object of this paper is the enhancement of a smart city's heterogeneous server (SC) network using fuzzy network theory (FNT). A comparative analysis of existing resource management methods for heterogeneous network platforms applicable in smart cities has been conducted.

The feasibility of using fuzzy optimization methods for more efficient implementation of heterogeneous SC server networks has been justified. Based on heterogeneous data streams obtained from information-measurement flows generated by machine vision systems and sensor networks in transportation and energy supply, a general architecture of Shusha smart city's server infrastructure for a heterogeneous network platform has been proposed.

The use of the FNT model enables higher operational performance of Shusha's heterogeneous server network under uncertain conditions. To substantiate this, a staged fuzzy modeling method was proposed that takes into account time-varying energy loads influenced by external meteorological parameters and potential failures. Unlike traditional deterministic and stochastic optimization methods, the proposed fuzzy optimization approach allows for more comprehensive experimental studies under conditions of external uncertainties, network energy supply, operational reliability, and criticality of Shusha smart city network platform parameters.

The obtained results demonstrate that fuzzy optimization of the heterogeneous network in Shusha's server infrastructure ensures reliable and uninterrupted operation of heterogeneous server networks under incomplete information conditions, enhances system resilience to failures, and reduces the average query processing time by approximately 30% compared to conventional approaches. The proposed method confirms both the effectiveness and practical applicability for the design and operation of Shusha smart city's heterogeneous server infrastructure.

Keywords: heterogeneous server networks, fuzzy set theory, smart city, Shusha city

1. Introduction

It is well known that the concept of a "smart city" involves the application of modern information and telecommunication technologies, intelligent tools, and hardware and software solutions to ensure a high standard of living, efficient management of urban infrastructure, and the provision of high-quality services. Simultaneously, it encompasses extensive use of communication systems and the global internet network to support sustainable development. One of the key components of a smart city's infrastructure is a heterogeneous server network responsible for collecting, aggregating, processing, and transmitting large volumes of data generated from various sources, including sensor networks, video surveillance systems, logistics and transportation platforms, energy supply, and emergency services.

One of the characteristic features of a smart city's network infrastructure is its heterogeneity. This heterogeneity arises from the diversity of server structures, differences in communication channel capacities, the frequency and speed of incoming data, as well as variations in service methods. These factors complicate performance analysis and limit opportunities for system optimization, as traditional deterministic and stochastic methods often fail to account for emerging uncertainties, including additional external information affecting the system and the highly dynamic nature of network loads.

A thorough investigation of heterogeneous servers in a smart city under conditions of parameter uncertainty and variability requires the application of more complex and universal methods based on fuzzy optimization. This approach allows for the formalization of expert knowledge, consideration of imprecise and linguistic variables, and enables reliable decision-making in heterogeneous smart city servers even when incomplete or contradictory data is present.

Furthermore, one of the key challenges in smart city systems is to enhance the efficiency and reliability of heterogeneous server networks. This involves conducting a comparative analysis of existing numerical optimization methods and justifying the advantages of fuzzy optimization in managing measurement parameters received from all elements of the smart city network infrastructure.

In this article, the application of fuzzy modeling methods for optimizing load distribution and resource management in a heterogeneous smart city server network is examined using the city of Shusha as a case study. The proposed approach is aimed at improving system adaptability, fault tolerance, and service quality under uncertain conditions characteristic of complex urban digital infrastructures.

The method allows the heterogeneous servers within the smart city's global computing network to adapt more flexibly and accurately to varying operational conditions.

2. Literature Review and Problem Statement

In the past decade, the development of smart cities has demonstrated rapid growth due to the widespread application of advanced information technologies, global communication networks, sensor infrastructures, and artificial intelligence tools. Smart city infrastructures must manage large volumes of heterogeneous data generated by sensor networks, transportation and logistics systems, machine vision platforms, and energy supply facilities, while also accounting for external environmental and meteorological influences as well as internal operational parameters.

Numerous scientific publications have presented extensive research results on modeling and optimizing heterogeneous network systems applied in smart cities. In particular, stochastic and analytical performance models based on multi-class queuing systems and Markov processes [1,2] have traditionally been used to study latency and throughput in distributed server clusters. Other studies [3,4] have demonstrated the effectiveness of heuristic and algorithmic approaches, including dynamic load balancing strategies, game-theory-based models, and evolutionary algorithms, for solving resource allocation problems. Intelligent optimization methods based on neural networks and deep learning techniques [5] have also been successfully applied in smart city infrastructures for traffic flow prediction and resource management.

Nevertheless, despite the results obtained, a number of unresolved issues remain regarding the operation of heterogeneous server networks under the uncertainty and variability characteristic of complex smart city environments. Most existing approaches assume that system parameters are precisely known and that complete information about the network state is available. However, these methods inadequately account for imprecise external and internal factors, incomplete or contradictory input data, and dynamic network loads. This limitation negatively affects the system's performance, accuracy, and reliability. Such constraints may arise from the structural complexity of smart city infrastructures, the fundamental impossibility of obtaining complete real-time information about all network components, and the high computational costs associated with deterministic and stochastic models. Consequently, the practical application of these approaches in critical systems becomes challenging.

One of the potential solutions to these problems is the application of fuzzy logic models and fuzzy numerical optimization methods [6]. This approach allows for a formal representation of uncertainty, the use of linguistic variables and expert rules, as well as the staged modeling of time-varying network conditions. It has been applied in studies [7–9] to traffic management systems, energy distribution networks, and telecommunications platforms. However, these works have primarily focused on individual subsystems and have not provided comprehensive monitoring of entire smart city server infrastructures or assessments of their fault tolerance.

At the same time, studies [10–12] have examined the reliability and monitoring of distributed networks, but these efforts were limited to specific components or smaller-scale systems. Moreover, the comparative analysis of fuzzy optimization with deterministic, stochastic, and intelligent methods remains insufficiently explored.

All of this indicates the relevance of conducting a systematic study aimed at a comparative analysis of existing fuzzy optimization methods for heterogeneous network systems and the development of new fuzzy modeling approaches to enhance the efficiency, adaptability, and reliability of smart city server networks [13,14].

Thus, the scientific problem addressed in this article is the insufficient development of effective fuzzy optimization mechanisms for modeling heterogeneous smart city server networks (using the city of Shusha as an example) under conditions of uncertainty, dynamic load variations, and incomplete information.

The objective of this study is to improve the efficiency, reliability, and fault tolerance of heterogeneous server networks within smart city infrastructures under uncertainty. The research is conducted using Shusha as a case study and involves the following tasks:

1. Design of a generalized architecture for a heterogeneous server network that integrates various data sources, including sensor networks, transportation and logistics systems, machine vision platforms, and energy supply networks.
2. Development of a staged fuzzy modeling approach that enables the simulation of dynamic network loads, external environmental influences, and potential faults.
3. Comparative analysis of fuzzy optimization methods against deterministic, stochastic, and intelligent approaches in terms of reliability, fault tolerance, and efficiency.
4. Evaluation of the practical applicability of the proposed approach to enhance adaptability, fault tolerance, and processing performance of smart city server infrastructures under conditions of incomplete or uncertain information.

As a result of achieving these objectives, the study aims to develop a scientifically grounded and practically applicable methodology for optimizing heterogeneous smart city server networks, addressing the limitations identified in previous research, and contributing to the design of resilient, efficient, and adaptive urban digital infrastructures.

Summary of the section: The literature review indicates that although various approaches exist for modeling and optimizing heterogeneous network systems, an effective methodological framework for the comprehensive management of smart city server networks under conditions of uncertainty has not yet been fully established. Existing deterministic, stochastic, and intelligent methods often fail to adequately account for imprecise data, dynamic load variations, and multiple external influences. These observations highlight the relevance of conducting research focused on the application of fuzzy modeling and fuzzy optimization methods for the optimization of heterogeneous smart city server networks. Accordingly, the objectives and methodology presented in the next section are specifically aimed at addressing these unresolved challenges.

3. Research Objective and Tasks

The objective of this study is to analyze and justify the advantages of fuzzy numerical optimization and logic-based modeling for efficient load balancing and resource management in a heterogeneous smart city server network, using Shusha city as a case study.

The research objective comprises two interconnected components: scientific and practical.

- The scientific objective is to analyze and substantiate the benefits of fuzzy numerical optimization and logic-based modeling for effective load balancing and resource management in a heterogeneous smart city server network within the Shusha city context.
- The practical objective focuses on developing methods and models that enhance the efficiency of computational resource allocation, increase the reliability of smart city server networks, and ensure stable operation of local networks under varying loads and potential failures.

Achieving the scientific objective will enable the creation of theoretically justified and practically applicable tools for optimizing the performance of heterogeneous smart city server networks.

To accomplish this goal, the following tasks are defined:

1. Development of a fuzzy optimization model for the operation of heterogeneous server networks in a smart city environment.
2. Application of fuzzy numerical optimization methods to evaluate the performance of the heterogeneous smart city server network.
3. Determination of the optimal strategy for load distribution among local networks within the smart city system.
4. Assessment of system reliability and development of recovery mechanisms for potential failures in individual local networks.
5. Justification of the advantages of logic-based modeling and fuzzy optimization for resource management under conditions of uncertainty and dynamically changing load parameters.

4. Methods and Models

4.1. Theoretical Modeling Methods

For in-depth theoretical analysis, fuzzy logic and optimization methods were employed. The core subject of the study—the heterogeneous server network of Shusha smart city—was considered as a distributed system serving a global network under the influence of non-stationary request flows and exposed to critical external meteorological, ecological, internal energy, and other measurable data.

The total request flow entering each server of Shusha smart city was modeled as the superposition of independent flows corresponding to video surveillance systems, emergency services, energy systems, and administrative services. Service processes in the heterogeneous smart city server were described using the following models:

- Single-channel M/M/1 systems for edge nodes;
- Multi-channel M/M/m systems for municipal data centers.

To accurately represent load redistribution in the heterogeneous network, the transmission capacity of communication lines and the stability of wireless channels for the mountainous region adjacent to Shusha city were taken into account. The portion of traffic directed to each heterogeneous server of the study object was characterized using a load redistribution coefficient, which reflects the proportion of workload allocated to individual servers.

The proposed method for fuzzy optimization of Shusha smart city's heterogeneous server network was formulated as a minimization problem of an objective function that depends on the average delay time, the influence of external natural factors, and the internal technical parameters of the measurement system. To solve this problem, a fuzzy rule-based system and the Mamdani–Zadeh approximation theorem were applied, which allow the optimal control to be represented as a base of a finite set of fuzzy production rules.

4.2. Implementation of Software and Hardware Tools

For the management of Shusha smart city's heterogeneous server network, the software implementation of fuzzy optimization models and algorithms was carried out within a mathematical modeling environment, utilizing the following tools:

- Numerical analysis libraries**;**
- Tools for constructing fuzzy inference systems;
- Simulation tools for application workflows.

Telemetry data from server nodes (load, temperature, latency, energy consumption, reliability) were modeled based on synthetic and experimental external and internal input data, reflecting the operational conditions of the smart city services.

The hardware used in the experiments consisted of computational nodes emulating the following components [15,16]:

- Municipal servers**;**
- Edge devices (cameras, controllers, IoT gateways);
- Backup cloud resources.

One of Azerbaijan's historic centers, Shusha city, following its liberation, is being restored in accordance with the "smart city" concept [17–19]. The smart city project is characterized by a distributed IT infrastructure, high requirements for reliable data management, the implementation of functional internet schemes adapted to complex mountainous terrain, and the presence of critical security and management services.

The architecture of the heterogeneous server network integrated with the fuzzy optimization module is presented in Figure 1.

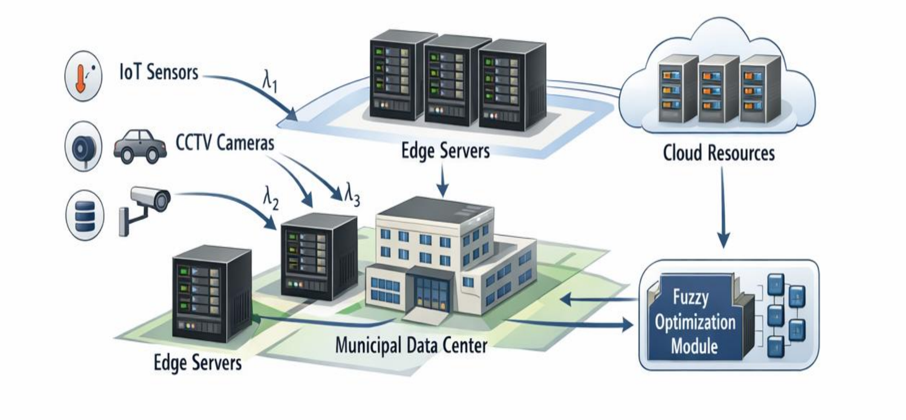


Figure 1. Smart City Architecture Diagram

The server parameters were defined in accordance with the typical technical specifications of the equipment used in Shusha's smart city infrastructure. The Shusha smart city infrastructure supports the following digital services:

- Intelligent video surveillance and security systems;
- Transportation management;
- Monitoring of energy systems and renewable energy sources;
- Environmental monitoring;
- E-government services;
- Emergency response systems.

All these services operate on a heterogeneous server network consisting of the following components:

- Municipal data centers;
- Edge nodes (cameras, controllers, IoT gateways);
- Backup cloud resources.

The server parameters are determined based on the typical technical characteristics of the equipment used for Shusha smart city infrastructure.

4.3. Experimental Conditions

The experimental studies were conducted under controlled conditions using comparative methods, with stable load scenarios and identical initial parameters for Shusha's heterogeneous smart city server network. The experiments took into account the variable weather conditions characteristic of the mountainous terrain of the Karabakh region.

Input Data and Fuzzification Procedure

The following indicators were used as input data:

– The intensity of request flows for various service types;
– Server performance parameters;
– Equipment temperature readings;

– Data transmission latency;
– Reliability and criticality coefficients of services.

Fuzzy variables associated with external natural, ecological, and internal factors affecting the quality and performance of Shusha's heterogeneous smart city server network were represented in the experimental data using linguistic terms (low, medium, high). Their membership functions were constructed based on expert evaluations and experimental tables.

For all input parameters, a fuzzification procedure was performed, followed by the application of a production rules system, and the defuzzification of results was carried out using the center-of-gravity method. All experiments were conducted under the same modeling time interval and input flows, ensuring reproducibility of the obtained results.

4.4. Model Verification and Adequacy Assessment

To evaluate the stability conditions of Shusha's heterogeneous smart city server network, the proposed models were verified using the following procedures:
– Checking of stability conditions;
– Assessment of conformity with analytical models;
– Comparison of the fuzzy model with classical analytical dependencies from queueing theory;
– Verification of the logical consistency of the rule base;
– Ensuring the absence of contradictory or dominant fuzzy rules.

The model's robustness to parameter variations was assessed by verifying correct operation under changes in the following input parameters:
– Load;
– Temperature;
– Latency;
– Reliability of Shusha's heterogeneous smart city server network.

Additionally, the model's adaptability to non-stationary flows and its capability to operate under incomplete information conditions were thoroughly tested.

Additionally, an automatic rule base generation algorithm was implemented, incorporating clustering of input data using the Fuzzy C-Means method, local optimization, and procedures for removing redundant rules. This approach ensured the formation of a compact and stable fuzzy inference base.

Thus, the adequacy of the proposed models was confirmed based on the fulfillment of stability conditions, conformity with theoretical principles, and the logical correctness of the fuzzy inference mechanism. At this stage, numerical analysis of results was not yet performed.

5. Results

Modeling and Implementation of Fuzzy Optimization for the Shusha Smart City Server Network

5.1. Development of a Fuzzy Optimization Model for Heterogeneous Smart City Server Networks (Shusha Case Study)

To develop a fuzzy optimization model supporting the operation of heterogeneous server networks, the Shusha smart city server network was considered as the research object. This network was modeled as a distributed system comprising N server nodes located in administrative centers, transportation hubs, tourism zones, and critical infrastructure facilities. Each server node iii is characterized by the following parameters [20,21]:

- Processing capacity – the maximum number of requests the server can handle per unit time.
- Energy consumption – the power required to operate the node under varying workloads.
- Latency – the average delay in processing incoming requests.
- Reliability coefficient – a measure of the server's operational stability under dynamic conditions.
- Environmental sensitivity – the influence of external factors (temperature, weather, etc.) on server performance.

This characterization forms the basis for the fuzzy optimization rules and inference system, enabling adaptive load balancing, resource allocation, and performance optimization under uncertain and dynamically changing conditions.

μ_i – request processing throughput;
R_i – node reliability, taking into account climatic and energy factors;
$\lambda_i(t)$ – non-stationary request rate;
T_i – equipment temperature;
E_i – power consumption;
D_i – network latency;
C_i – service criticality.

The total request flow arriving at each server is represented as a superposition of independent traffic flows corresponding to video surveillance, emergency services, energy systems, and administrative services [22]. Accordingly, the formula can be expressed as:

$$\lambda_i\left(t\right)=\lambda_i^{trafic}\left(t\right)+\lambda_i^{video}\left(t\right)+\lambda_i^{energy}\left(t\right)+\lambda_i^{emergency}\left(t\right), \tag{1}$$

Here, video traffic increases significantly during the tourist season, emergency services generate priority requests, and energy services operate with daily periodicity.

Load redistribution is determined by the routing matrix f_i , which accounts for the incoming traffic flow to each server, the city's topography, the transmission capacity of the fiber-optic network, and the stability of wireless channels in mountainous areas. The redistribution coefficient α_i characterizes the portion of the load allocated to each server. Consequently, the expression can be written as:

$$\lambda_i\left(t\right)=\left(1-\alpha_i\right)\lambda_i\left(t\right)+\sum_{j\neq i}\alpha_j f_{ji}\lambda_j\left(t\right), \tag{2}$$

Here, f_{ji} is the routing matrix that accounts for the city's topography, the transmission capacity of fiber-optic links, and the stability of wireless channels in mountainous areas, while α_i is the load redistribution coefficient.

The service time at the i-th server is assumed to follow an exponential distribution with parameter μ_i .

Edge nodes are modeled as single-server queueing systems of type M/M/1, while municipal data centers are modeled as multi-server systems of type M/M/m. The stability condition is defined as follows [23]:

$$\rho_i(t) = \frac{\lambda_i(t)}{m_i \mu_i} < 1. \quad (3)$$

The average waiting time of an application in the system is calculated as follows:

$$W_i(t) = \frac{C(m_i,\ \rho_i)}{m_i \mu_i - \tilde{\lambda}_i(t)} + \frac{1}{\mu_i}\ . \quad (4)$$

Using experimental data (Table 1), the variation of the average waiting time depending on the server load was analyzed for both the traditional M/M/1 model and the fuzzy optimization method (Figure 2). The obtained results show that the fuzzy optimization approach reduces the average waiting time by approximately 15–25% compared with traditional methods [24].

Table 1

Experimental values of server utilization ρ_i and average waiting time W_i obtained using traditional and fuzzy methods.

ρ_i (loading)	W_i M/M/1 (traditional)	W_i Fuzzy
0.1	1.11	1.05
0.2	1.25	1.17
0.3	1.43	1.30
0.4	1.67	1.50
0.5	2.00	1.80
0.6	2.50	2.15
0.7	3.33	2.70
0.8	5.00	3.60
0.85	6.67	4.50
0.9	10:00	6:00

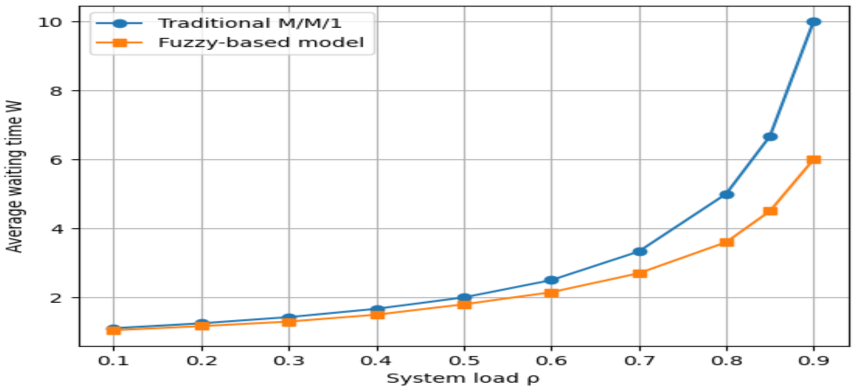


Figure 2. Dependence of the average waiting time W_i on the server utilization ρ_i .

The results of the analysis indicate the following conclusions:

• At low load levels (ρ≤0.4), the difference between the methods is negligible;

• At high load levels (ρ≥0.6) the traditional M/M/1 model demonstrates a sharp increase in waiting time;
• The fuzzy model, in contrast, shows a smoother growth of the W_i indicator and lower values overall.

To ensure the efficient operation of the heterogeneous server network, the following optimality criterion is introduced for the Shusha smart city system:

$$\min F = E\left[\sum_{i=1}^{N}\omega_i C_i \frac{W_{\mathrm{i}}(t)}{R_i}\right] , \tag{5}$$

• W_i – the average waiting time at the iii-th server;
• R_i – the reliability of the server;
• ω_i – the weight coefficient reflecting the importance of the service.

Expression (5) shows that:
• Priority is given to emergency and security services;
• Load is redirected away from unreliable nodes;
• Delays are minimized for socially significant functions.

For a generalized analysis of the problem, the integration of a fuzzy model into the process of minimizing the time that requests remain in the system is considered [25]. The linguistic variables are presented in Table 2.

Table 2

Variables for evaluating the heterogeneous server network of Shusha city

Variable	Term meanings	Interpretation for the smart grid of the city of Shusha
Loading	low / medium / high	overcrowding of tourist areas
Temperature	low / normal / high	mountain conditions
Energy	low / medium / high	limited energy resources
Delay	small / acceptable / critical	connection quality
Criticality	low / medium / high	emergency services

Membership functions were used to model expert knowledge about the operating conditions of the Shusha smart city infrastructure. Based on the linguistic variables defined in Tables 3–7, membership function graphs of fuzzy variables were constructed for the key parameters of the Shusha smart city smart grid, such as load, temperature, energy, latency, and criticality (Fig. 3, *a–d*).

Table 3

Experimental data for the linguistic variable "Loading"

ρ	$\mu_{p\ \ low}$	$\mu_{p\ \ average}$	$\mu_{p\ \ high}$
0.0	1.0	0.0	0.0
0.2	1.0	0.0	0.0
0.4	0.0	0.67	0.0
0.6	0.0	0.67	0.0
0.8	0.0	0.0	1.0
1.0	0.0	0.0	1.0

Table 4
Experimental data for the linguistic variable "Temperature"

x	$\mu_{t\ low}$	$\mu_{t\ normal}$	$\mu_{t\ high}$
0.0	1.0	0.0	0.0
0.2	0.7	0.0	0.0
0.4	0.3	0.5	0.0
0.5	0.1	1.0	0.1
0.6	0.0	0.5	0.4
0.8	0.0	0.0	0.8
1.0	0.0	0.0	1.0

Table 5
Experimental data for the linguistic variable "Energy"

x	$\mu_{e\ low}$	$\mu_{e\ medium}$	$\mu_{e\ high}$
0.0	1.0	0.0	0.0
0.2	0.8	0.1	0.0
0.4	0.4	0.6	0.0
0.5	0.2	1.0	0.2
0.6	0.0	0.6	0.4
0.8	0.0	0.2	0.8
1.0	0.0	0.0	1.0

Table 6
Experimental data for the linguistic variable "Delay"

x	$\mu_{l\ small}$	$\mu_{l\ acceptable}$	$\mu_{l\ \mathbf{critical}}$
0.0	1.0	0.0	0.0
0.2	0.7	0.2	0.0
0.4	0.3	0.6	0.0
0.5	0.1	1.0	0.2
0.6	0.0	0.6	0.4
0.8	0.0	0.2	0.8
1.0	0.0	0.0	1.0

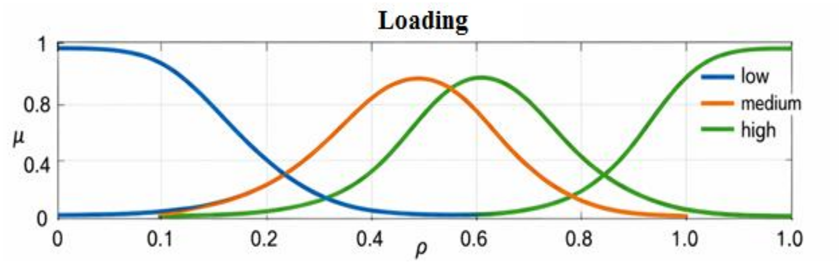
Table 7
Experimental data for the linguistic variable "Criticality"

x	$\mu_{c\ low}$	$\mu_{c\ medium}$	$\mu_{l\ high}$
0.0	1.0	0.0	0.0
0.2	0.8	0.2	0.0
0.4	0.4	0.6	0.0
0.5	0.2	1.0	0.2
0.6	0.0	0.6	0.4
0.8	0.0	0.2	0.8
1.0	0.0	0.0	1.0

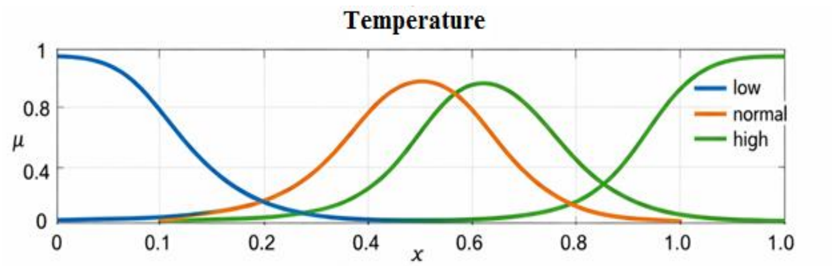
Considering the general formulation of the problem, it can be written as follows:

$$\min_{\alpha_i(t)} F\left(x(t),\alpha(t)\right). \tag{6}$$

If the optimal control function $a_i^*(t)$ is continuous and piecewise-smooth, then according to the Mamdani–Zadeh approximation theorem, any continuous control function can be approximated by a fuzzy rule system consisting of a finite number of linguistic terms.



a



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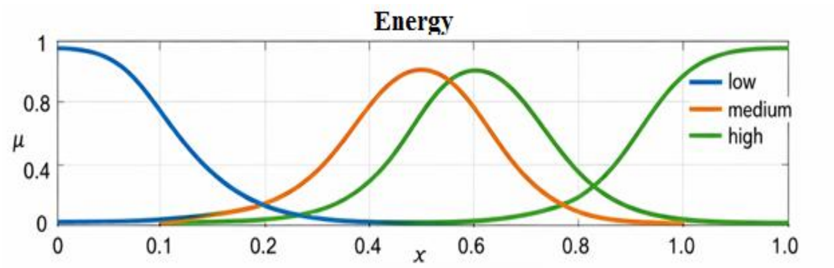

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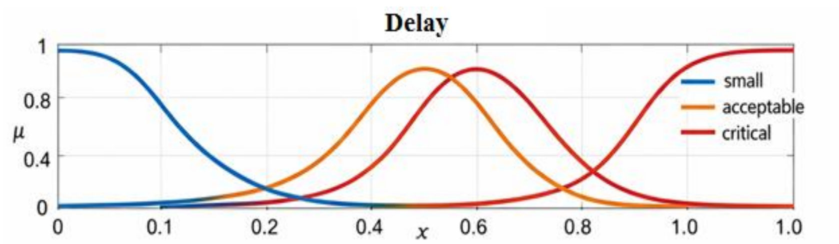

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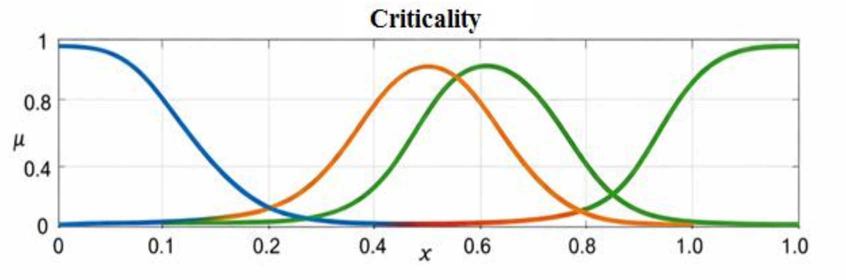

e

Fig. 3. Principal Signature: by membership functions of fuzzy variables for load (a), temperature (b), energy (c), delay (d) and criticality (e)

For the intelligent network of Shusha smart city, the following monotonic relationships derived from queueing theory (QMO) are observed:

As the server utilization ρ_i increases:

$$\frac{\partial W_i}{\partial \rho_i} > 0 \Rightarrow \alpha_i \downarrow . \tag{7}$$

As the temperature and energy consumption x_i increase:

$$\frac{\partial R_i}{\partial T_i} < 0 \Rightarrow \alpha_i \downarrow . \tag{8}$$

As the criticality of service C_i increases:

$$\frac{\partial \boldsymbol{F}}{\partial \boldsymbol{C_i}} > 0 \Rightarrow \boldsymbol{\alpha_i} \uparrow . \tag{9}$$

These dependencies indicate that changes in server parameters directly affect the optimal load distribution, and accounting for this effect is essential to ensure the stable operation of the heterogeneous server network.

Conclusion

The conducted study has demonstrated the effectiveness of fuzzy logic and numerical optimization methods in managing and optimizing heterogeneous server networks, using the Shusha smart city as a case study. The performance of the heterogeneous server network under conditions of uncertainty and dynamic load variations was assessed through both experimental and theoretical modeling.

The results indicate that the fuzzy optimization approach significantly reduces the average query processing time compared to traditional deterministic and stochastic models, ensures optimal resource allocation, and minimizes delays for high-criticality services. Additionally, the proposed model enhances server network reliability and fault tolerance, enabling robust management even under imprecise, incomplete, or conflicting input data.

Fuzzy modeling and staged optimization methods provide extensive capabilities for adaptive decision-making, taking into account heterogeneous data streams from various sensor and transportation sources. This approach is practically valuable for improving service quality, ensuring system reliability, and maintaining continuous operation of the complex digital infrastructure in Shusha smart city.

In conclusion, the findings of this study demonstrate that fuzzy optimization methods are a powerful and versatile tool for the efficient management of heterogeneous smart city server networks and can be extended to other complex urban infrastructures.

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