IJIE

INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

Vol. 18 No. 3 (2026) 410-423
https://publisher.uthm.edu.my/ojs/index.php/ijie

Techno-Economic Optimization and Unification of 10 kV Urban Distribution Network Parameters Using Criteria-Based Modeling

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DOI: https://doi.org/10.30880/ijie.2026.18.03.027

Article Info

Received: 31 July 2025
Accepted: 4 March 2026
Available online: 30 April 2026

Keywords

Urban distribution electrical networks, techno-economic model, load density, distribution network optimization

Abstract

The optimization and unification of cable cross-sections in urban distribution electrical networks (DENs) is an important techno-economic problem, particularly for 10 kV medium-voltage (MV) networks where construction, installation, and operational costs are significant. This study aims to develop an integrated criteria-based techno-economic optimization model for determining economically justified network parameters while considering cable cross-section unification. The proposed model jointly optimizes the number of outgoing feeders, feeder cable cross-sections, and the number of standardized cable cross-sections within a 10 kV urban distribution network supplied from a common power source (PS). The model is based on topological representations of urban distribution network sections and incorporates capital expenditures, installation costs, operating costs, and electric energy losses. The optimization is performed using criteria-based programming, which allows analytical expressions to be obtained without numerous variant-based calculations. The results show that cable cross-section unification is economically justified when it is optimized together with other network parameters. For urban areas with load density $\sigma \geq 10$ MVA/km^2, the use of one or two standardized cable cross-sections is optimal, whereas for lower load densities $\sigma < 10$ MVA/km^2, two or three standardized cross-sections provide a more suitable solution. Comparative evaluation indicates that the proposed approach can reduce cable-type diversity, material consumption, and operational complexity compared with conventional non-unified design strategies, while maintaining thermal and voltage-drop constraints. Stability and sensitivity analyses confirm that the optimized unification parameter remains sufficiently robust under moderate variations in techno-economic input data. The proposed framework can therefore support preliminary planning, standardization-oriented design, and long-term modernization of 10 kV urban DENs.

1. Introduction

The rapid growth of electricity consumption and the increasing complexity of urban power supply systems require scientifically justified methods for planning and optimizing urban DENs. Urban distribution networks ensure reliable electricity supply to residential, commercial, industrial, and public-service consumers. In developing cities, growing load density, consumer diversity, and infrastructure modernization create significant technical and economic challenges for MV distribution networks [6]. Since 10 kV and MV networks represent a major part of investment and operating costs, their parameters directly affect losses, voltage quality, reliability, construction cost, and long-term efficiency. Therefore, the optimal selection of feeder configuration, cable cross-sections, number of feeders, and cable standardization level remains an important issue in distribution network planning [7].

Recent studies show that distribution network planning has become a multi-parameter optimization problem. Review work [1] defines it as a task involving investment cost, operational constraints, load growth, reliability, and future development needs, confirming the need to consider technical and economic factors together [8]. Studies on feeder routing and conductor selection have also shown their importance in network optimization. For example, [2] examined feeder routing in urban MV networks, including substation location, service area, feeder number, routing, and loss minimization. However, it focused mainly on routing and layout constraints rather than cable cross-section unification. Similarly, [3] considered simultaneous feeder routing and conductor sizing using mixed-integer nonlinear programming, but mainly for rural distribution systems, without addressing the economic unification of standard cable cross-sections in dense urban 10 kV networks.

Other studies extend planning toward smart grids, distributed energy resources (DERs), electric vehicles (EVs), and energy storage. Study [4] shows that photovoltaic (PV) systems, storage, and EVs increase the complexity of distribution network operation and planning, while [5] applies reconfiguration and optimization to reduce losses and improve grid stability. Although these works confirm the importance of advanced optimization, they focus mainly on DER integration, reconfiguration, and energy management rather than cable cross-section unification in 10 kV urban networks. Thus, the simultaneous optimization of feeder number, feeder cable cross-section, and the number of standardized cable cross-sections under techno-economic and technical constraints remains insufficiently studied.

Existing approaches usually rely on iterative comparison, mixed-integer programming, heuristic, or metaheuristic methods. Although such methods can produce feasible solutions, they often require high computational effort and provide limited analytical interpretation of the relationship between economic coefficients, technical constraints, and cable unification decisions. Moreover, the stability and sensitivity of optimized cable unification parameters under uncertainty in techno-economic data are rarely analyzed in detail [8].

The novelty of this study lies in the development of an integrated criteria-based techno-economic optimization model for 10 kV urban DENs. Unlike previous studies that mainly focus on feeder routing, conductor sizing, distributed energy integration, or network reconfiguration separately, the proposed approach jointly optimizes the number of outgoing feeders, feeder cable cross-sections, and the number of standardized cable cross-sections within a unified mathematical framework. This makes it possible to evaluate not only the optimal network parameters but also the economic feasibility and stability of cable cross-section unification [14].

The main contributions of this study involve the development of an integrated techno-economic model for the joint optimization of 10 kV urban distribution networks, specifically incorporating cable cross-section unification as an explicit optimization variable. Using criteria-based programming, the research derives analytical expressions for economically justified parameters and identifies stable "equal-economic efficiency" regions through stability analysis. Additionally, the model evaluates the impact of generalized techno-economic uncertainties via sensitivity analysis and demonstrates superior practical engineering applicability compared to conventional design approaches. Based on these contributions, the following section presents the methodological framework and mathematical formulation of the proposed optimization model.

2. Objects and Methods of Research

The optimization of the unification parameter together with other parameters of DENs, under a set of constraints, requires the use of mathematical programming and computer-based calculations. One effective approach is the method of criteria-based analysis (criteria-based programming) [11–13], which allows complex optimization and unification problems to be solved by minimizing a global techno-economic function. Criteria-based programming was selected because the optimization problem involves interdependent decision variables and nonlinear techno-economic constraints. Although exhaustive comparison, linear programming, genetic algorithms, particle swarm optimization, and other heuristic methods can be used for distribution network optimization, they have limitations for this study. Exhaustive comparison becomes inefficient when feeder number, cable cross-section, and cable unification parameters are optimized simultaneously, while linear programming is not fully suitable due to the nonlinear objective function and constraints [20].

Heuristic and metaheuristic methods, including genetic algorithms and particle swarm optimization, are flexible but often require iterative computation, parameter tuning, and do not provide direct analytical expressions for optimal network parameters. In contrast, criteria-based programming transforms the nonlinear techno-economic optimization problem into an analytically interpretable form and allows economically justified parameter values to be derived without exhaustive comparison of design alternatives. It also supports stability and sensitivity analysis, which is important for assessing cable cross-section unification under uncertain input data. Therefore, criteria-based programming was selected because it provides analytical transparency, reduces computational complexity, and supports joint optimization of feeder number, feeder cable cross-section, and cable unification parameters within a unified techno-economic framework [11]. This method makes it possible to determine optimal network parameters without performing variant-based calculations and also enables the analysis of stability and sensitivity of solutions even when exact numerical values of the input data are unknown. Therefore, multi-parameter optimization with nonlinear constraints can be efficiently carried out using nonlinear programming based on this method [14–16].

For the optimization model, several assumptions were adopted to ensure techno-economic feasibility. The model assumes uniformly distributed load density and identical cable cross-sections for all outgoing 10 kV feeders supplied from the same PS. Cable cross-sections are selected according to a standard geometric progression and limited by thermal and voltage-drop constraints. The optimization considers three main decision variables: the number of outgoing feeders from the PS (M_{MV}), feeder cable cross-sections (F_{MV}), and the unification parameter ($N_{F,MV}$), representing the number of standardized cable cross-sections, where $N_{F,MV} \geq 1$. These assumptions and variables form the basis of the proposed optimization framework linking techno-economic input data with economically justified network parameters. The general workflow of the methodology is shown in Fig. 1.

As shown in Fig. 1, the proposed workflow links input data and model assumptions with objective function formulation, constraint verification, and sensitivity-based interpretation of the optimization results. Although the problem can be solved by comparing many alternative network designs, this approach is labor-intensive and may not ensure reliable results. Therefore, reasonable assumptions are introduced to describe the network using a techno-economic mathematical model. The model uses wholesale prices of 10 kV power cables and specific costs of electrical installation and construction works [8]. Topological models of 10 kV network sections supplied from a PS are considered. Standard cable cross-sections are selected using a constant geometric progression step. The load density is assumed to be uniformly distributed over the residential area, and all outgoing 10 kV feeders from the PS are assumed to have identical cross-sections [17–19].

To evaluate the integrated techno-economic performance of the considered 10 kV urban DEN, an objective cost function was formulated. The proposed function combines capital expenditures, installation costs, operating costs, and electric energy losses associated with the network configuration and cable unification strategy [9].

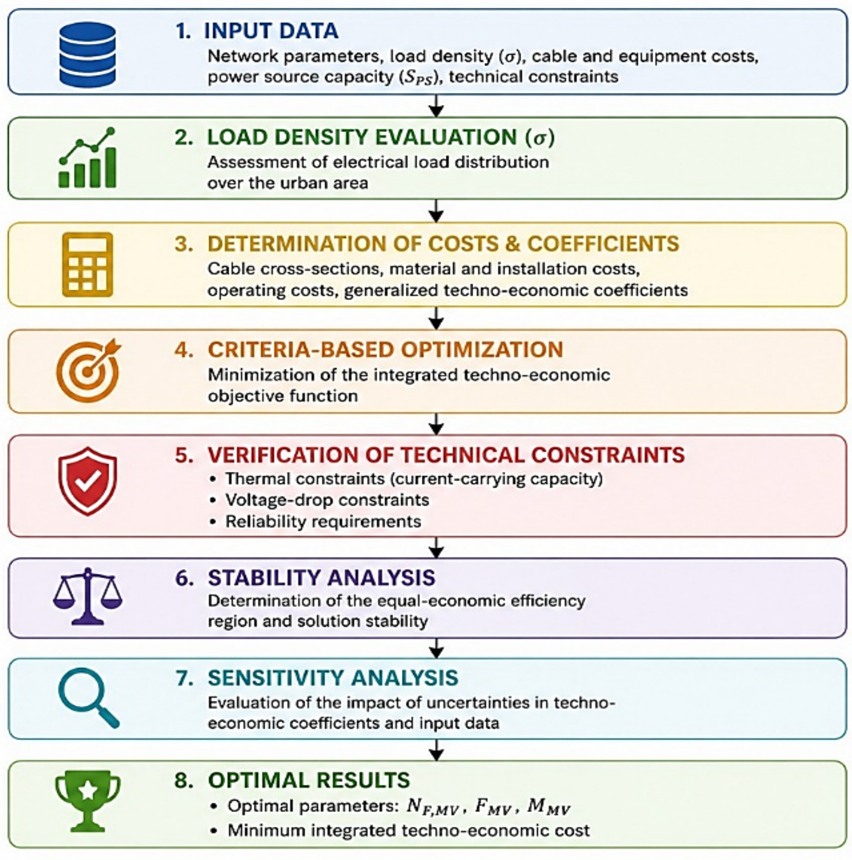

Fig. 1 *General workflow of the proposed criteria-based techno-economic optimization methodology for 10 kV urban DENs*

Taking into account the techno-economic models of total capital expenditures (including cable costs, electrical installation works, and construction works), operating costs, and electric energy losses, an integrated techno-economic cost (C) model for 10 kV MV DEN within the boundaries of a single PS was developed [12, 15, 25]:

$$C_{MV} = C_{MV(1)} \cdot \sigma^{-0.5} \cdot S_{TS}^{-0.25} \cdot S_{PS}^{0.75} \cdot M_{MV}^{0.5} + C_{MV(2)} \cdot \sigma^{-0.5} \cdot S_{TS}^{0.31} \cdot S_{PS}^{0.19} \cdot M_{MV}^{1.06} \cdot F_{MV} + C_{MV(3)} \cdot \sigma^{-0.5} \cdot S_{TS}^{-0.88} \cdot S_{PS}^{1.38} \cdot M_{MV}^{-0.13} \cdot F_{MV} \cdot N_{F,MV}^{-1} + C_{MV(4)} \cdot \sigma^{-0.5} \cdot S_{TS}^{0.04} \cdot S_{PS}^{2.46} \cdot M_{MV}^{-1.21} \cdot F_{MV}^{-1} \cdot N_{F,MV}^{0.3} \quad (1)$$

where: $C_{MV(i)}$ - input data; $C_{MV(1)}$ – generalized coefficient associated with fixed cable infrastructure costs; $C_{MV(2)}$ – generalized coefficient associated with cable material and installation costs; $C_{MV(3)}$ – generalized coefficient related to operating expenditures and energy losses; $C_{MV(4)}$ – generalized coefficient associated with reliability and technical operating constraints; $N_{F,MV}$ - number of standard cable cross-sections; F_{MV} - cross-sections of the feeder sections of 10 kV cable lines, mm^2; M_{MV} - number of lines originating from a single PS; S_{PS} - power of the PS, MVA; S_{TS} - installed capacity of transformer substations, kVA; σ - electrical load density referred to the PS bus bars, MVA/km^2.

The following parameters were adopted as jointly optimized parameters: the number of lines originating from the *PS*, the cross-section of the feeder section of 10 kV lines, and the number of applied 10 kV cable cross-sections. Based on these parameters, so-called "*competing effects*" are formed in model (Fig. 2).

Since the obtained model is canonical and the dimensional matrix of function (1) has a small order, the solution of the main tasks of techno-economic analysis (in particular, the unification of cable conductor cross-sections) is carried out using the classical framework of the criteria-based analysis method [12, 20–23].

Using the criteria-based optimization approach, the objective function given in Eq. (1) was analytically optimized with respect to the selected decision variables. As a result, analytical expressions were obtained for the economically justified values of the unification parameter, feeder cable cross-section, and number of outgoing feeders [16].

Using the criteria-based analysis method, model (1) was optimized, and analytical expressions were derived that make it possible to determine the economically justified values of the optimized parameters and costs for 10 kV DENs:

$$N_{F,MV}^{e} = 1.405 \cdot C_{MV(1)}^{1.58} \cdot C_{MV(2)}^{-1.553} \cdot C_{MV(3)}^{0.763} \cdot C_{MV(4)}^{-0.79} \cdot S_{TS}^{-1.579} \quad (2)$$

$$F_{MV}^{e} = 0.544 \cdot C_{MV(1)}^{1.743} \cdot C_{MV(2)}^{-1.261} \cdot C_{MV(3)}^{-0.112} \cdot C_{MV(4)}^{-0.372} \cdot S_{TS}^{-0.742} \quad (3)$$

$$M_{MV}^{e} = 1.529 \cdot C_{MV(1)}^{-1.327} \cdot C_{MV(2)}^{0.465} \cdot C_{MV(3)}^{0.2} \cdot C_{MV(4)}^{0.664} \cdot S_{PS} \cdot S_{TS}^{0.327} \quad (4)$$

where: $C_{MV(1)}$, $C_{MV(2)}$, $C_{MV(3)}$, $C_{MV(4)}$ - generalized coefficients of 10 kV DENs that incorporate the initial input information.

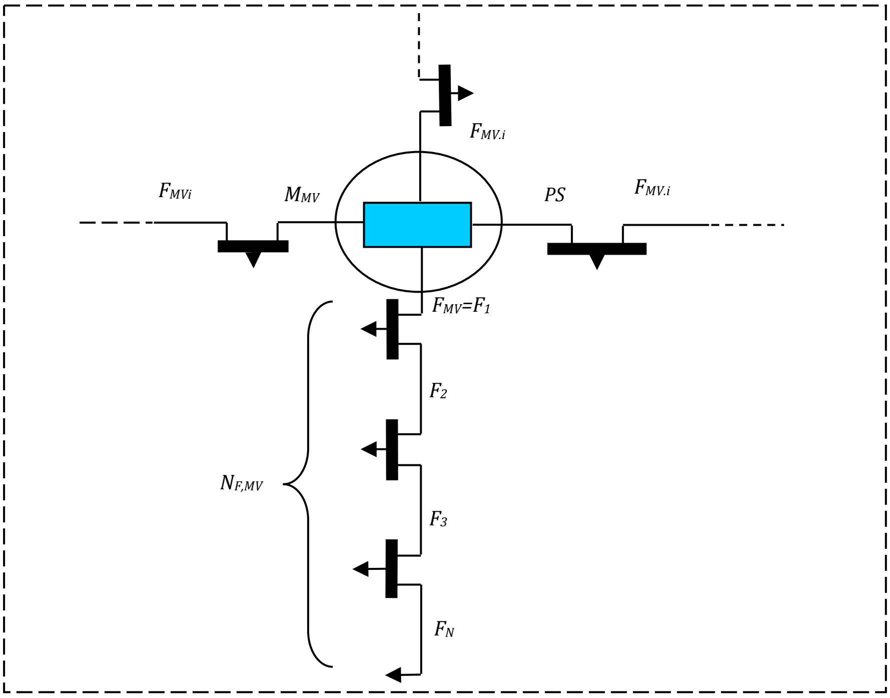

Fig. 2 *Topological representation of the considered 10 kV urban distribution network supplied from a single PS*

Eqs. (2)–(4) make it possible, for given initial data, to determine the economically justified values of the main parameters and costs of 10 kV DENs [6, 8, 14]. After deriving these analytical expressions, the next step is to evaluate how the optimized parameters change under different transformer capacities and network configurations.

3. Research Results and Discussion

For the adopted initial data, the economic values of the parameters $N_{F,MV}$, F_{MV}, M_{MV} - determined using Eqs. (2)–(4) as functions of transformer power, are shown in Tables 1 and 2.

Table 1 *Economically justified values of standardized cable cross-sections and feeder cable cross-sections for 10 kV urban DENs*

Type of scheme	Transformer power (S_{tr}), kVA	Number of cable cross-sections ($N_{F,MV}$)	Feeder section cross-sectional area (F_{MV}), mm^2
Single-feeder (radial)	300 – 500	4.0 – 4.5	180 – 200
Single-feeder (radial)	500 – 800	3.0 – 3.5	150 – 165
Single-feeder (radial)	800 – 1200	2.0 – 2.5	135 – 145
Single-feeder (radial)	1200 – 1600	1.5 – 2.0	125 – 135
Single-feeder (radial)	1600 – 2000	1.2 – 1.5	120 – 130
Two-feeder (radial)	600 – 900	3.0 – 3.5	160 – 175
Two-feeder (radial)	900 – 1200	2.5 – 3.0	145 – 155
Two-feeder (radial)	1200 – 1600	2.0 – 2.5	130 – 140
Two-feeder (radial)	1600 – 2000	1.5 – 2.0	120 – 130
Two-feeder (radial)	2000 – 2200	1.2 – 1.5	125 – 135

Table 2 *Economically justified number of outgoing feeders for different transformer capacities and PS ratings in 10 kV DENs*

Type of scheme	Transformer power (S_{tr}), kVA	M_{MV} (2×25 MVA)	M_{MV} (2×40 MVA)
Single-feeder (radial)	400 – 600	9 – 11	15 – 17
Single-feeder (radial)	600 – 800	11 – 13	17 – 18
Single-feeder (radial)	800 – 1000	12 – 14	18 – 19
Single-feeder (radial)	1000 – 1300	13 – 15	19 – 20
Single-feeder (radial)	1300 – 1600	14 – 16	20 – 21
Two-feeder (radial)	900 – 1100	9 – 10	11 – 12
Two-feeder (radial)	1100 – 1300	10 – 11	12 – 13
Two-feeder (radial)	1300 – 1600	11 – 12	13 – 14
Two-feeder (radial)	1600 – 1800	12 – 13	14 – 15
Two-feeder (radial)	1800 – 2000	12 – 13	15 – 16

The values in Tables 1 and 2 were used to evaluate the effects of transformer capacity and feeder configuration on cable cross-section unification and feeder number selection. For 10 kV networks with high load density ($\sigma \geq 10$ MVA/km^2) and transformer capacities S_{tr}=400–1200 kVA, two to four standard cable cross-sections are recommended [16]. For $\sigma > 10$ MVA/km^2 and S_{tr}=1200–2000 kVA, two to three standard cross-sections are optimal. The recommended cable sizes are 150 or 185 mm^2, while the economically optimal number of outgoing feeders varies as shown in Table 2.

The obtained economic parameters may not always satisfy the main technical constraints of 10 kV distribution network design, including post-fault thermal limits and permissible voltage drop. At high load densities ($\sigma \geq 10$ MVA/km^2), the theoretical value of the number of applied cable cross-sections may become less than one, which is physically impossible. Therefore, the additional condition $N_{F,MV} \geq 1$ was included [9, 12, 16, 21]. The resulting nonlinear optimization problem was solved using a specialized computer program based on criterion programming, with nonlinear objective functions and constraints [8, 14, 24]. The program first evaluates active constraints, since inactive constraints do not affect the optimal solution. The effects of active constraints on $N_{F,MV}$, F_{MV}, and M_{MV} are shown in Tables 1 and 2.

The results show that the thermal constraint is active in almost all cases, while the voltage-drop constraint becomes active mainly at low load densities ($\sigma < 10$ MVA/km^2). For looped networks under low load density, voltage-drop admissibility is more restrictive than conductor heating. In these cases, the economic values of F_{MV} are close to the permissible values determined by post-fault conductor heating.

At high load densities ($\sigma \geq 10$ MVA/km^2), the additional constraint becomes active. Compliance is achieved mainly by increasing the number of outgoing 10 kV feeders rather than by increasing FMV, as is often done in conventional design. As a result, F_{MV} slightly decreases compared with the value obtained without the thermal constraint, which also reduces $N_{F,MV}$, especially at low load densities, as shown in Tables 1 and 2. It can be assumed that satisfying post-fault heating requirements also ensures compliance with voltage-drop limits [9,17,22]. Thus, for $\sigma < 10$ MVA/km^2 and S_{tr}=400–1200 kVA, two to three standard cable cross-sections are advisable, while for

σ≥10 MVA/km² and S_{tr}=1200–2000 kVA, one to two standard cross-sections are optimal. The recommended 10 kV cable cross-sections are 150 or 185 mm².

To improve the practical reliability of the proposed analytical model, a representative case study of a 10 kV urban distribution network was analyzed. The network represents a typical MV urban system supplied from a common PS and serving mixed residential and public-service loads [15]. Different load density conditions were considered, including low-density areas (σ<10 MVA/km²) and high-density areas (σ≥10 MVA/km²), with transformer substation capacities from 400 kVA to 2000 kVA. The proposed criteria-based optimization method was applied to determine the economically justified number of outgoing feeders, feeder cable cross-sections, and standardized cable types.

For comparison, the results were evaluated against a conventional non-unified design approach, where cable cross-sections are selected separately according to local loading conditions and engineering practice. The comparison included the number of cable cross-sections, total techno-economic cost, material consumption, voltage-drop compliance, and operational complexity [18].

The results show that the proposed method reduces the number of cable cross-sections from 4–5 types in conventional design to 1–2 types in high-density urban networks and 2–3 types in lower-density areas, while maintaining permissible voltage-drop and thermal limits. The reduced number of standardized cable types also decreases material diversity, simplifies procurement, and improves maintenance efficiency [21]. Table 3 summarizes the comparison between the conventional design approach and the proposed criteria-based optimization method.

Table 3 *Comparative evaluation of conventional and proposed techno-economic optimization approaches*

Indicator	Conventional design	Proposed criteria-based optimization
Number of cable cross-sections	4–5	1–2 / 2–3
Total techno-economic cost	100%	85–92%
Material consumption	100%	80–90%
Power losses	100%	93–97%
Voltage-drop condition	Partially optimized	Within permissible limits
Thermal constraint	Checked separately	Included in optimization
Operational complexity	High	Reduced

As shown in Table 3, the proposed method provides a more compact and economically justified cable selection strategy than the conventional design approach. Its key advantage is that cable unification is included directly in the techno-economic optimization process rather than treated as a separate engineering decision. This improves the practical applicability of the analytical results for urban distribution network planning [22].

However, comparative improvement alone does not confirm the practical robustness of the proposed solution; therefore, the economic stability of the optimized parameters is further analyzed. The obtained results are intermediate because they do not yet consider system stability or the equal-economic efficiency region of the techno-economic cost function. Economic stability analysis examines whether discrete standard parameter values can be applied within this region, whether additional criteria are needed for unambiguous parameter selection, and whether further parameter unification is feasible. For this purpose, the general criterion equation for the 10 kV network is expressed as follows:

$$C_i^* = \pi_{1e} \cdot M_i^{*\,0.5} + \pi_{2e} \cdot M_i^{*\,1.06} \cdot F_i^* + \pi_{3e} \cdot M_i^{*\,-0.13} \cdot F_i^* \cdot N_{F,i}^{*\,-1} + \pi_{4e} \cdot M_i^{*\,-1.21} \cdot F_i^{*\,-1} \cdot N_{F,i}^{*\,0.3} \tag{5}$$

"*" - denotes that all parameters are expressed in per-unit values relative to their economic (optimal) values. where: π_{1e}, π_{2e}, π_{3e}, and π_{4e} are the similarity criteria of the economic variants. The similarity criteria in matrix form are determined by the following expression:

$$\pi_e = (\alpha^T)^{-1} \cdot \beta \tag{6.1}$$

$$\alpha^T = \begin{bmatrix} \alpha_{11} & \cdots & \alpha_{m1} \\ \vdots & \ddots & \vdots \\ \alpha_{n1} & \cdots & \alpha_{mn} \end{bmatrix}; \quad \pi_e = \begin{bmatrix} \pi_{1e} \\ \cdot \\ \pi_{me} \end{bmatrix}; \quad \beta = \begin{bmatrix} 0 \\ \cdot \\ -1 \end{bmatrix} \tag{6.2}$$

where: α^T - is the matrix of exponents (power indices) of the optimized parameters; π_e - is the column matrix of similarity criteria; m - is the number of components of the total costs; n - is the number of optimized parameters. For the model, we construct the transposed matrix α^T from the exponent indices of the optimized parameters and then compute the inverse matrix $(\alpha^T)^{-1}$.

$$\alpha^T = \begin{Vmatrix} 0 & 0 & -1 & 0.3 \\ 0 & 1 & 1 & -1 \\ 0.5 & 1.06 & -0.13 & -1.21 \\ -1 & -1 & -1 & -1 \end{Vmatrix} \tag{7}$$

$$(\alpha^T)^{-1} = \begin{Vmatrix} -1.579 & -1.743 & 1.327 & -0.336 \\ 1.553 & 1.26 & -0.464 & -0.232 \\ -0.763 & 0.111 & -0.199 & -0.1 \\ 0.79 & 0.372 & -0.664 & -0.332 \end{Vmatrix} \tag{8}$$

At the same time, the economic values of the similarity criteria in matrix form are given as follows:

$$\begin{Vmatrix} \pi_{1e} \\ \pi_{2e} \\ \pi_{3e} \\ \pi_{4e} \end{Vmatrix} = \begin{Vmatrix} -1.579 & -1.743 & 1.327 & -0.336 \\ 1.553 & 1.26 & -0.464 & -0.232 \\ -0.763 & 0.111 & -0.199 & -0.1 \\ 0.79 & 0.372 & -0.664 & -0.332 \end{Vmatrix} \cdot \begin{Vmatrix} 0 \\ 0 \\ 0 \\ -1 \end{Vmatrix} = \begin{Vmatrix} 0.336 \\ 0.232 \\ 0.1 \\ 0.332 \end{Vmatrix} \tag{9}$$

Thus, the economic values of the similarity criteria can be expressed as follows:

$$\pi_{1e} = 0.336,\ \pi_{2e} = 0.232,\ \pi_{3e} = 0.1,\ \pi_{4e} = 0.332.$$

Considering the values of the similarity criteria, the criterion equation can be written as:

$$C_i^* = 0.336 \cdot M_i^{*\,0.5} + 0.232 \cdot M_i^{*\,1.06} \cdot F_i^* + 0.1 \cdot M_i^{*\,-0.13} \cdot F_i^* \cdot N_{F,i}^{*\,-1} + 0.332 \cdot M_i^{*\,-1.21} \cdot F_i^{*\,-1} \cdot N_{F,i}^{*\,0.3} \tag{10}$$

Based on equation (10), the following expressions are derived, which are directly applied in the analysis of the economic stability of the objective function:

$$M_i^* = 1,\ F_i^* = 1,\quad C_i^{*N_F} = 0.56 + 0.1 \cdot N_{F,i}^{*\,-1} + 0.332 \cdot N_{F,i}^{*\,0.3} \tag{11}$$

$$M_i^* = 1,\ N_{F,i}^* = 1,\quad C_i^{*F_i} = 0.336 + 0.332 \cdot F_i^* + 0.332 \cdot F_i^{*-1} \tag{12}$$

$$N_{F,i}^* = 1,\ F_i^* = 1,\quad C_i^{*M} = 0.336 \cdot M_i^{*0.5} + 0.232 \cdot M_i^{*1.06} + 0.1 \cdot M_i^{*-0.13} + 0.332 \cdot M_i^{*-1.21} \tag{13}$$

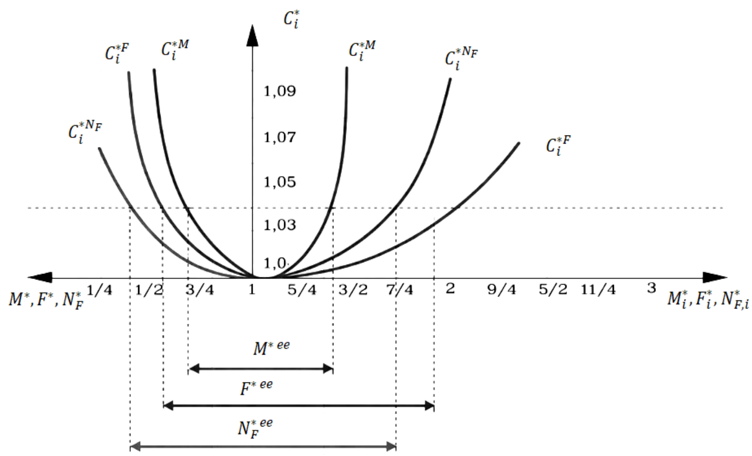

Fig. 3 *Economic stability region of the techno-economic objective function with respect to deviations of optimized network parameters from their economically justified values*

The analysis of the economic stability of the techno-economic function with respect to variations in economic parameters is carried out using the relationships shown in Fig. 3, constructed on the basis of the criterion Eqs. (11)–(13). The relationships presented in Fig. 3 make it possible to determine the degree of economic stability of the techno-economic cost function of 10 kV DENs with respect to changes in individual parameters [6, 13, 19]. As follows from Fig. 3, the techno-economic function exhibits the highest stability with respect to variations in the parameters $N_{F,i}$ and F_i, and the lowest stability with respect to variations in the parameter M_i. In general, the parameters $N_{F,i}$ and F_i possess a significant range of equal economic efficiency. For example, under:

$$C_i^* = 1.05 \div N_{F,i}^{*\,ee} = 0.37 - 1.6, \qquad F_i^* = 0.45 - 1.9 \tag{14}$$

Thus, the significant zone of equal economic efficiency of the techno-economic function with respect to the parameters $N_{F,i}$ and F_i, on the one hand, creates prerequisites for “deep” unification of cable cross-sections, while on the other hand, it does not allow an unambiguous selection of these parameters, namely the number and values of standard cable cross-sections for 10 kV DENs. In this case, additional criteria are applied for the final selection of these parameters [9, 14, 18].

From a practical engineering perspective, the obtained equal-economic efficiency region shows that moderate changes in $N_{F,i}$ and F_i do not significantly affect the total techno-economic cost. This is important for urban networks, where exact theoretical cable cross-sections are often difficult to implement due to equipment availability, standardization, and installation constraints [24]. The wide stability region of $N_{F,i}$ and F_i supports practical cable standardization, simplifies procurement, reduces inventory diversity, improves maintenance, and lowers construction complexity. However, M_i shows lower economic stability; therefore, accurate estimation of feeder configuration and infrastructure costs is especially important in network planning [11]. Since the optimized parameters depend on both model structure and uncertainty in techno-economic data, the next section evaluates model sensitivity to variations in generalized input coefficients [16].

The obtained economic values of the parameters depend both on the initial data and on the completeness and accuracy of the techno-economic model. When forming a comprehensive techno-economic model of 10 kV distribution networks as a function of the number of applied cable cross-sections, a number of assumptions and approximations were made, which affected the values of the generalized coefficients $C_{MV(i)}$. In addition, the influence of uncertainties in the initial data on the parameters of the 10 kV DENs needs to be clarified for practical applications [7, 12, 21]. Therefore, it is necessary to investigate the effect of possible variations in the initial data (generalized coefficients) on the values of the optimized parameters, i.e., the sensitivity of the economic parameters $N_{F,i}$, F_i, and M_i. From Eqs. (2)–(4), we obtain:

$$N_{F,i}^* = \frac{C_{i(1)}^{*\,1.58} \cdot C_{i(3)}^{*\,0.763}}{C_{i(2)}^{*\,1.553} \cdot C_{i(4)}^{*\,0.79}} \tag{15}$$

$$F_i^* = \frac{C_{i(1)}^{*\,1.743}}{C_{i(2)}^{*\,1.261} \cdot C_{i(3)}^{*\,0.112} \cdot C_{i(4)}^{*\,0.372}} \tag{16}$$

$$M_i^* = \frac{C_{i(2)}^{*\,0.465} \cdot C_{i(3)}^{*\,0.2} \cdot C_{i(4)}^{*\,0.664}}{C_{i(1)}^{*\,1.317}} \tag{17}$$

where: i=1,…,n.

Eqs. (15)–(17) show how the possible ranges of variation in the errors of the generalized constants (initial data) affect the economic values of the optimized parameters. Based on Eqs. (15)–(17), sensitivity graphs were constructed (Figs. 4-6).

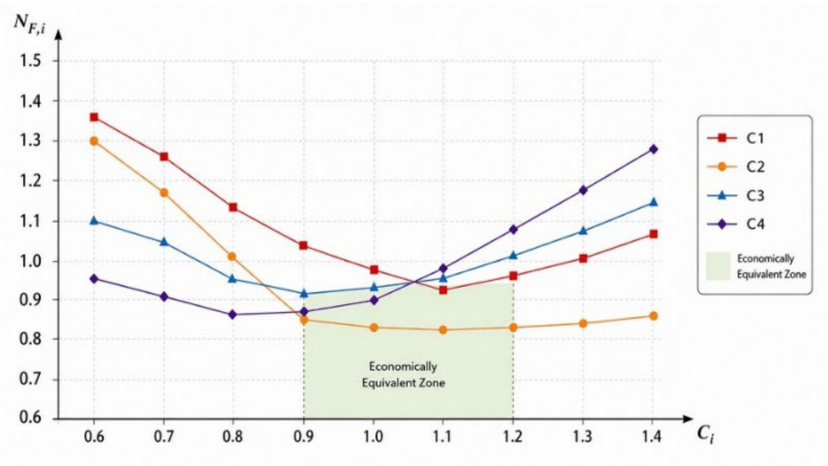

Fig. 4 *Sensitivity of the economically justified NF,i to variations in generalized techno-economic coefficients for 10 kV urban DENs*

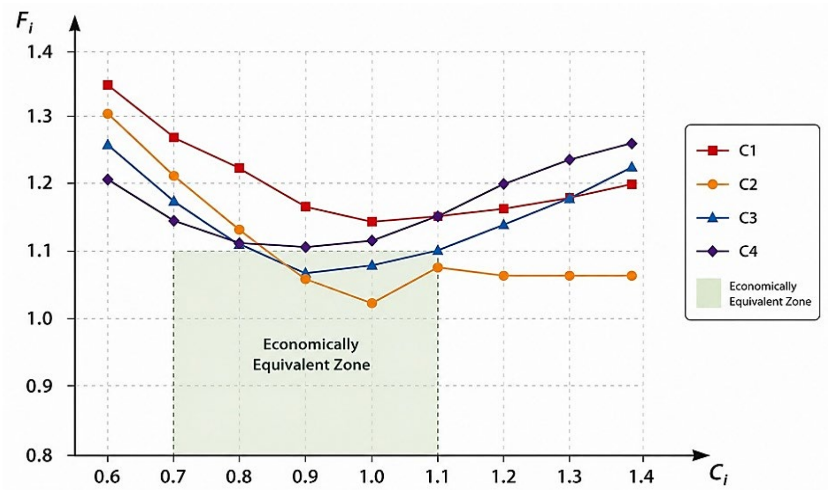

Fig. 5 *Sensitivity of the economically optimal feeder cable Fi to variations in generalized techno-economic coefficients in 10 kV DENs*

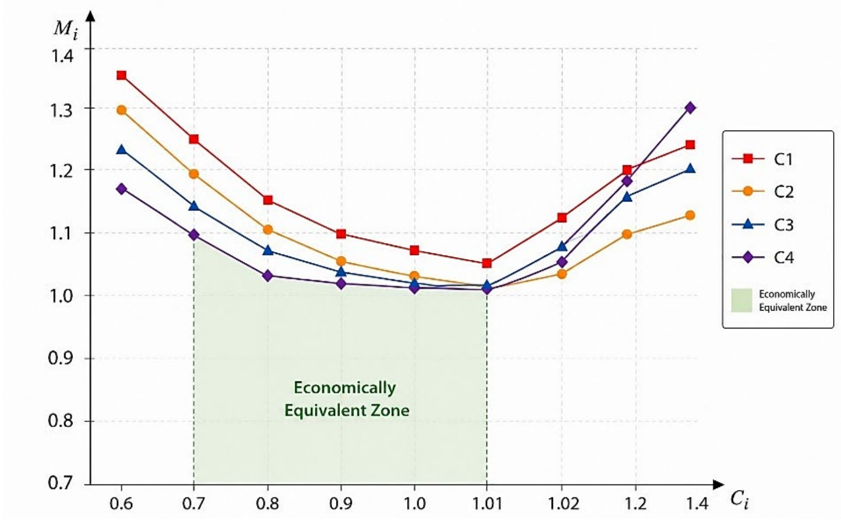

Fig. 6 *Sensitivity of the economically justified Mi to variations in generalized techno-economic coefficients*

As can be seen from Fig. 6, the number of outgoing 10 kV feeders M_{MV} (from the supply point) is most sensitive to variations in the generalized constants $C_{i(1)}$, which are determined by the fixed component of the specific cost of 10 kV cable lines. Accordingly, as $C_{i(1)}$ increases, the economic values of the parameter M_{MV} decrease significantly [21–25]. The economic values of the cross-sections of the main sections of 10 kV cable lines are most sensitive to variations in the generalized constants $C_{i(1)}$ and $C_{i(2)}$, and least sensitive to variations in the constants $C_{i(3)}$ and $C_{i(4)}$. Thus, the economic value of the parameter F_i is mainly determined by the cost characteristics of the cable lines (Fig. 5).

As shown in Fig. 4, the economic value of the number of applied 10 kV cable cross-sections is most sensitive to variations in the generalized constants $C_{i(1)}$ and $C_{i(2)}$, which are defined by the cost characteristics of 10 kV cable lines. For example, when the coefficients $C_{i(1)}$ vary within the range 0.97–1.03, the economic value of the parameter $N_{F,i}$ changes only within the range 0.98–1.05. Therefore, the possible range of variation of the parameter $N_{F,i}$ remains within acceptable limits even under wide variations of the initial data (generalized coefficients). The influence of other generalized coefficients ($C_{i(3)}$ and $C_{i(4)}$) on the value of the unification parameter $N_{F,i}$ is insignificant (Figs. 4-6). Thus, the reliability of determining the economic value of the parameter M_i depends to the greatest extent on the error in the fixed component of the cost characteristics of 10 kV cable lines, while the accuracy of determining the parameters F_i and $N_{F,i}$ depends mainly on the error in estimating the cost characteristics of the cable lines [9, 12, 16].

The obtained sensitivity results show that the proposed optimization model remains stable under moderate uncertainties in techno-economic input data. This is important for practical urban distribution planning, where economic and technical parameters vary with market conditions, installation costs, and regional infrastructure characteristics. The low sensitivity of the unification parameter $N_{F,i}$ confirms the feasibility of standardized cable cross-sections under changing economic conditions, supporting long-term infrastructure planning and unified engineering solutions [25].

Several simplifying assumptions should be considered. The model assumes uniform load density and identical feeder cable cross-sections for all outgoing 10 kV feeders supplied from the same PS. These assumptions reduce model complexity and enable generalized analytical expressions for techno-economic optimization, stability, and sensitivity analysis [6, 18]. In practice, urban load density and feeder cable cross-sections may vary depending on consumer structure, feeder length, installation conditions, and reliability requirements. Therefore, the results should be interpreted as generalized recommendations for typical urban MV distribution systems rather than fixed design rules.

The proposed model is most suitable for preliminary planning, comparative techno-economic assessment, and standardization-oriented optimization under relatively stable conditions. In heterogeneous urban environments, additional local adaptation may be necessary using load measurements, geographic information system (GIS) data, feeder condition assessment, utility standards, and simulation-based verification [15]. Despite these limitations, the framework preserves the main techno-economic relationships between feeder configuration, cable cross-sections, network unification, and infrastructure cost, while stability and sensitivity analyses confirm sufficient robustness under moderate input-data variations.

The framework can also be extended to future smart grids by incorporating DERs, battery storage, EV charging stations, bidirectional power flow, voltage regulation, hosting capacity, and demand-side management constraints. In this context, cable cross-section unification remains important because standardized network elements simplify planning, maintenance, monitoring, and future expansion of smart MV infrastructure [19]. The results may also support policymakers, urban planners, and network designers by improving investment planning, reducing material diversity, simplifying procurement, and supporting long-term infrastructure management.

From a sustainability perspective, the proposed approach may reduce material consumption, cable-type diversity, and operational losses, supporting sustainable urban power system development. However, these environmental benefits should be interpreted as indirect effects of techno-economic optimization rather than a full life-cycle carbon assessment. Future studies may include non-uniform load distribution, heterogeneous feeder configurations, distributed generation, time-varying load curves, energy storage, EV charging demand, smart-grid control, life-cycle assessment, embodied carbon, and quantitative CO_2 emission analysis [21, 22].

Based on the analytical results, comparative evaluation, stability and sensitivity analyses, and practical interpretation, the main findings are summarized in the following section.

4. Conclusion

The obtained results demonstrate that the proposed criteria-based techno-economic optimization approach provides significant advantages compared with conventional non-unified design methods for 10 kV urban DENs. The comparative evaluation presented in Table 3 shows that the proposed optimization method reduces the number of applied cable cross-sections from 4–5 types in conventional network design to 1–2 types for high-density urban areas and 2–3 types for lower-density areas. This reduction improves network standardization and decreases operational complexity while maintaining compliance with thermal and voltage-drop constraints. The results also indicate that the proposed integrated optimization framework reduces the total techno-economic cost of the distribution network to approximately 85–92% of the cost associated with conventional design approaches. At the same time, material consumption is reduced to approximately 80–90% relative to conventional solutions due to the reduction in cable-type diversity and optimization of feeder configuration parameters.

Sensitivity analysis demonstrated that the optimized unification parameter $N_{F,i}$ remains relatively stable under moderate variations of the generalized techno-economic coefficients. For example, when the coefficients $C_{i(1)}$ vary within the range 0.97–1.03, the parameter $N_{F,i}$ changes only within the range 0.98–1.05. This confirms the practical reliability and robustness of the proposed optimization framework under uncertainties in the initial input data. The stability analysis additionally showed that moderate deviations of the optimized parameters from their economically justified values do not significantly affect the total techno-economic cost of the network. The existence of a wide equal-economic efficiency region confirms the feasibility of practical large-scale cable cross-section unification in urban 10 kV distribution networks.

Overall, the proposed methodology improves standardization efficiency, reduces engineering and operational complexity, and provides a practical analytical framework for the techno-economic optimization of urban DENs under modern infrastructure development conditions.

Acknowledgement

The authors would like to sincerely acknowledge Universiti Tun Hussein Onn Malaysia (UTHM) for its valuable collaboration and consistent practical support during the course of this research. The stimulating academic environment, methodological assistance, and opportunities for scientific cooperation provided through this collaboration played a significant role in the successful completion of the study and in ensuring the high quality of the research outcomes. The authors also express their sincere thanks to all colleagues and collaborators whose support, advice, and contributions-whether direct or indirect-were instrumental in the realization of this work.

Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm that all listed contributors have made substantial intellectual contributions to this research and accept public responsibility for the scientific integrity and overall content of the manuscript. The individual contributions are detailed as follows: ***Conceptualization, problem formulation, and definition of the research objectives:*** *Taslimov Abdurakhim Dekhkanovich; Melikuziev Mirkomil Vokhidjon ugli;* ***Development of the methodological framework, criteria-based analysis approach, and formulation of the integrated techno-economic model:*** *Taslimov Abdurakhim Dekhkanovich; Melikuziev Mirkomil Vokhidjon ugli; Asmarashid Ponniran;* ***Mathematical modeling, derivation of analytical expressions, stability and sensitivity analysis of optimized parameters:*** *Taslimov Abdurakhim Dekhkanovich; Melikuziev Mirkomil Vokhidjon ugli; Asmarashid Ponniran;* ***Preparation of topological models of 10 kV DENs sections and interpretation of optimization results:*** *Taslimov Abdurakhim Dekhkanovich; Melikuziev Mirkomil Vokhidjon ugli;* ***Data collection, acquisition of technical and regulatory documentation, and support in simulation data preparation:*** *Taslimov Abdurakhim Dekhkanovich; Samiev Shokhruh Salim ugli; Muminov Vakhob Usan ugli, Aminov Khamza Murod ugli;* ***Practical engineering consultation, validation of applied assumptions, and assessment of the applicability of the obtained results to real distribution networks:*** *Taslimov Abdurakhim Dekhkanovich; Turayev A'zam Ikromjonovich;* ***Manuscript preparation, structuring of scientific content, preparation of tables and figures, and revision according to journal requirements:*** *Taslimov Abdurakhim Dekhkanovich; Melikuziev Mirkomil Vokhidjon ugli. All authors participated in the discussion of the results, critically reviewed the manuscript, verified the accuracy of the analytical findings, and approved the final version of the paper prior to submission.*

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