Decision Science Letters 13 (2024) 461–470

Contents lists available at GrowingScience

Decision Science Letters

homepage: www.GrowingScience.com/dsl

A novel scenario planning approach considering criteria interaction in multi-criteria evaluation: An application to urban mobility

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C H R O N I C L E

Article history:
Received: October 10, 2023
Received in revised format: November 20, 2023
Accepted: January 4, 2024
Available online: January 4, 2024

Keywords:
Scenario Planning
Scenario Evaluation
Multiple Criteria
Interaction
Scenario Selection
Urban Mobility

A B S T R A C T

This study proposes a new scenario planning approach which consists of two main stages: evaluating scenarios under multiple criteria and selecting a manageable number of representative scenarios covering a wide range of future developments. In the evaluation stage, the interaction between criteria has been considered, which offers a significant contribution both to the scenario literature and practice. In the selection stage, a mathematical programming model has been developed to ensure the selection of distinct scenarios with high evaluation values. The approach is applied to an urban mobility system in a metropolitan area. The selected scenarios provide valuable insights into the future of urban mobility, serving as a basis for identifying strategies. The proposed approach does not offer a solution only for scenario planning problems, it can be effectively applied to similar problems in different areas.

1. Introduction

Scenario planning has been recognized as a valuable approach for strategic planning to address uncertainty by exploring possible future scenarios (Stead & Banister, 2003; Stojanović et al., 2014). Since decisions made today will affect the future performance of a system, foreseeing future developments and challenges is a prerequisite for success in future plans. Rather than accurately predicting the future, scenario planning studies support dealing with unexpected and challenging future developments (Enoch et al., 2020). Scenarios can help strategic planners to build a sustainable system by exploring how future events may evolve through addressing uncertainties, providing insight into long-term impact of decisions and, revealing opportunities and threats.

A scenario represents a combination of potential developments in the future (Bood & Postma, 1997). Scenarios can be constructed by qualitative approaches such as deductive methods (Ramírez & Selin, 2014) or by using combinations of future projections (Schoemaker, 1995). However, qualitative research often focuses on exploring complex phenomena in-depth, but it may provide limited breadth of information (Behling et al., 1980). To reduce complexity and difficulty in the evaluation phase of scenarios, building scenarios based on combinations of future developments is more appropriate due to their decomposable structure (Gausemeier et al., 1998).

To be able to evaluate and compare scenarios, various criteria have been suggested. The common criteria in the literature to evaluate scenarios are plausibility, consistency, probability, novelty, relevance, completeness, transparency, and diversity (Amer et al., 2013). Despite the variety of quality criteria, many quantitative methods in which scenarios can be decomposed into simpler future states (e.g. projections) commonly use plausibility, consistency and diversity (i.e. distance) (Gausemeier et al., 1998; Tietje, 2005; Lord et al., 2016). Based on the values obtained through these criteria, an elimination procedure is implemented to derive a manageable number of scenarios. This is often necessary, since in a scenario study, there can be

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doi: 10.5267/dsl.2024.1.002

thousands or even millions of scenarios depending on the number of factors and their alternative future states. Therefore, the number of scenarios should be reduced before initiating the strategic planning process to reduce complexity. However, most of the methods perform elimination procedures that consider the criteria only sequentially to evaluate scenarios. This leads to the loss of valuable information about possible futures. Using sequential elimination or relying only on a single criterion might result in ignoring some significant scenarios that might occur in the future.

Scenario planning begins with identifying significant factors relevant to the area of concern and their projections which are different future developments of factors. Each scenario is constructed by combining one projection from each factor. All the combinations create the scenario set. Scenarios can be thought of as alternatives in a typical multi criteria decision making (MCDM) problem. The scenarios are needed to be evaluated with respect to criteria. In this respect, it is similar to MCDM problems. However, since there are too many scenarios in a scenario planning practice, depending on the number of factors and their projections, and scenarios are based on various projections, it is really hard and complex to evaluate scenarios directly. So it will be more appropriate to evaluate projections and then aggregate their values. This approach offers an advantage for the simplification of the evaluation process. The framework of the problem is given in Fig. 1.

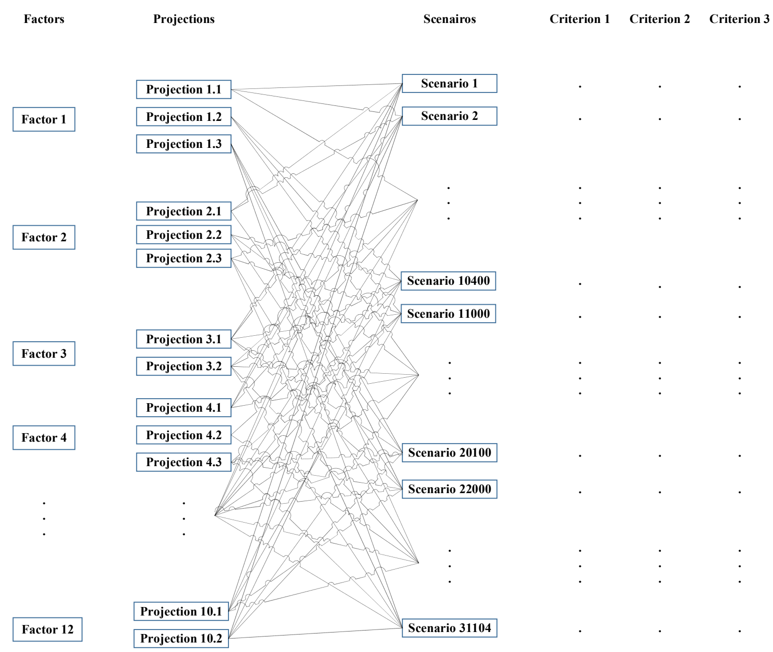

Fig. 1. Scenario building and evaluation structure

Table 1
Related Studies

Source	Quality Criterion / Criteria	Multiple Criteria Consideration	Criteria Interaction	Criteria for Scenario Elimination	Scenario Selection Method and Criteria
(De Kluyver & Moskowitz, 1984)	Probability	×	×	Probability	Optimization based on probability
(Gausemeier et al., 1998)	Consistency	×	×	Consistency	Cluster analysis based on similarity
(Tietje, 2005)	Consistency and distance	✓ (Sequentially)	×	Consistency	Optimization based on distance
(Mazzorana et al., 2009)	Consistency and distance	✓ (Sequentially)	×	Consistency	Optimization based on distance
(Lord et al., 2016)	Plausibility and diversity	✓ (Sequentially)	×	Plausibility	Optimization based on diversity
(Seeve & Vilkkumaa, 2022)	Consistency and diversity	✓ (Sequentially)	×	Consistency	Optimization based on diversity
Proposed Approach	Plausibility, Sustainability, Adaptability, Consistency, Dissimilarity	✓ (Simultaneously)	✓	Plausibility, Sustainability, Adaptability, Consistency	Optimization based on dissimilarity

To address the limitations in the literature (the most relevant papers are given in Table 1 for comparison purposes), a novel approach is proposed to improve scenario evaluation and selection process in this study. The main contribution of the scenario evaluation process lies in obtaining scenario values by considering multiple criteria and their interactions. Criteria that may appear insignificant on their own can have a substantial impact on the system when considered jointly, therefore, interactions play a crucial role in determining the outcomes of various systems (Kadaifci et al., 2020). By considering the weights of individual as well as joint criteria, the values of future projections are expected to be more accurate and representative due to reduced information loss. To calculate joint weights of criteria, a Sugeno λ-measure based approach is presented. Choquet integral is used to aggregate multiple criteria assessments considering their interactions. Following the scenario evaluation process, scenario selection is performed by means of a mathematical programming model to select a set of scenarios which cover a wide range of future developments. This minimizes the risk of overlooking diverse possible future developments. Proposed approach is applied to an urban mobility system in a metropolitan area, where uncertainties are high due to many uncontrollable factors. Exploring scenarios for long-term planning in metropolitan areas is crucial for gaining insights into future transportation needs, modes and technologies.

The rest of the paper is organized as follows. The theoretical basis of fuzzy measure and the Choquet integral, and the methodology of the proposed approach are described in Sections 2 and 3, respectively. An application about the evaluation and selection of urban mobility scenarios is presented in Section 4. Finally, conclusions and limitations of the study are provided in Section 5.

2. Theoretical Basis of the Proposed Approach

2.1. Sugeno λ-measure

The suggested method incorporates a fuzzy (i.e. non-additive) measure to evaluate scenarios based on multiple criteria. Therefore, it would be useful to briefly describe a fuzzy measure.

A fuzzy measure does not follow the usual rules of addition. That means, the total measurement may not simply be the sum of the individual measurements, as interactions or relationships between the parts play a significant role in determining the overall measurement. By considering the interactions between parts, fuzzy measures provide a more comprehensive understanding of the properties being measured. There are different types of fuzzy measures. λ-measure, as one of the well-known fuzzy measures (Mohamed & Xiao, 2003), was proposed by Sugeno (1977) to decrease the complexity of the decision making process. λ-measure allows us to calculate the measure of any set of elements taking into account interactions among them with the unique parameter λ if the measures of any two partitions of the set are known. In this way, the λ-measure captures the complex dependencies and interactions between different subsets of elements in the set. However, λ value is unique for all subsets. Fuzzy measure and λ-measure are defined as follows in Definitions 1 and 2, respectively:

Definition 1: (Sugeno, 1974) Let X be a finite set and a fuzzy measure μ defined on X be a set function $\mu: P(X) \rightarrow [0,1]$, where $P(X)$ is the power set of X. It has following properties:

i. Boundary, $\mu(\emptyset) = 0, \mu(X) = 1$.
ii. Monotonicity, $\mu(A) \leq \mu(C)$ if $A \subseteq C$.

Definition 2: Let $X = \{x_1, x_2, x_3, \ldots, x_n\}$ be a finite set and consider $\lambda \in (-1, \infty)$, λ-measure is a function $g_\lambda : 2^X \rightarrow [0, 1]$ such that it satisfies the following conditions:

i. $g_\lambda(X) = 1$
ii. If $A, B \in 2^X$ then $g_\lambda(A \cup B) = g_\lambda(A) + g_\lambda(B) + \lambda g_\lambda(A) g_\lambda(B)$ with $A \cap B = \emptyset$

Using these properties, Eq. 1 is obtained to find the unique value of λ on the interval (Leszczyński et al., 1985).

$$\lambda + 1 = \prod_{i=1}^{n}(1 + \lambda g_i), \text{ where } g_i = g_\lambda(x_i) \quad (1)$$

2.2. Choquet Integral

Choquet integral (Choquet, 1954) is a non-additive aggregation operator that relies on fuzzy measures (Ridaoui & Grabisch, 2016). It combines multiple criteria values into a single value representing individual weights of criteria and also interactions among them. In many application areas especially decision making, there exist interactions among criteria or elements (Shieh et al., 2009). Choquet integral (*ChI*) is a more appropriate aggregation function for such problems than classical operators such as weighted sum and ordered weighted averaging to produce more accurate results. The basic definitions are given as follows:

Definition 3: (Grabisch, 1995) Let μ be a fuzzy measure on the set $X = \{x_1, x_2, x_3, \ldots, x_n\}$. The ChI of a function $f: X \rightarrow [0, \infty]$ w.r.t. fuzzy measure μ is defined as:

$$\int f \, dg = \sum_{i=1}^{n}\big(f(x_i) - f(x_{i-1})\big)\mu(A_i) \quad (2)$$

where the indices $i = 1, 2, 3, \ldots, n$ represents the position of permutated function $0 \leq f(x_1) \leq f(x_2) \leq f(x_3) \leq \cdots \leq f(x_n)$, $f(x_0) = 0$ and $A_i \subseteq X$.

3. Proposed Approach

In this study, a novel approach is proposed to evaluate and select scenarios to be used in the strategic planning process. As explained in Section 1, scenarios are representations of possible developments that arise from a variety of factors. Possible developments of each factor are described by future projections and a scenario is constructed by combining one projection from each factor. Since scenarios could not be evaluated efficiently as a whole due to their complex structures, they are evaluated based on these projections. This is essential for simplifying the evaluation process. Projections are assessed with respect to multiple criteria and the assessments are aggregated using *ChI* which considers joint criteria weights that represent interactions between criteria. A new Sugeno λ-measure based approach is suggested for the calculation of joint criteria weights. Then, the overall value of each scenario is calculated using aggregated projection pairs weighted by their consistency. Since the number of scenarios might be excessive based on the number of factors and projections, it is crucial to select a representative set of scenarios that effectively covers the future and ensures a manageable number of scenarios. Accordingly, a mathematical programming model is developed to address this combinatorial problem. In summary, the proposed approach provides a systematic framework for scenario evaluation and selection that can help decision makers take part in strategic planning. The steps of the approach are given below:

Step 1. Identifying factors, their projections and criteria: First, factors and their possible future projections relevant to the problem area are identified, then, related quality criteria are determined based on expert opinions and literature review. The factors are denoted by the set $F = \{ft_1, \ldots, ft_I\}$ and the set of projections of factor i are $ft_i = \{p_{i1}, \ldots, p_{iJ}\}$, where $ft_i \in F$, factor indices $i = 1, \ldots, I$ and level indices $j = 1, \ldots, J$. The criteria are represented by the set $C = \{c_1, \ldots, c_U\}$, where $c_u \in C$ and indices $u = 1, \ldots, U$.

Step 2. Assessment of projections and criteria weights: Projections are assessed with respect to the determined criteria and experts assign individual weights to each criterion based on a predefined scale. The value of the projection p_{ij} w.r.t criterion c_u and the weight of the criterion c_u represented by fuzzy measures are denoted by $f_{p_{ij}}(c_u)$ and $\mu(c_u)$ $(i.e.\ \mu_{c_u})$.

Step 3. Calculation of joint criteria weights: The Sugeno λ-measure is a widely used method to calculate joint criteria weights. However, it may be restrictive due to using a single parameter value for all interactions. Each criteria subset has its own unique relationship, so it needs to have a specific λ value. To address this issue, a new method is proposed to calculate joint criteria weights considering different λ values for each criteria subset. Experts provide assessments using rating scale corresponding to criteria interactions in the interval [0,1]. Using Eq. 3, joint criteria weights are calculated by satisfying the fuzzy measure properties.

$$\mu_E = max\ (\mu_A + \ \mu_B + \lambda_E\, \mu_A\, \mu_B) \tag{3}$$

where $\forall E \subseteq X, \forall A, B \subset E, |A| \leq |B| < |E|$, $A \cap B = \emptyset$ $(i.e.\ \mu_{123} = \max(\mu_1 + \ \mu_{23} + \lambda_{123}\, \mu_1\, \mu_{23},\ \mu_2 + \ \mu_{13} + \lambda_{123}\, \mu_2\, \mu_{13},\ \mu_3 + \ \mu_{12} + \lambda_{123}\, \mu_3\, \mu_{12})$. The *max* function is performed to satisfy the monotonicity property. If $\mu_X \neq 1$, the weights are normalized using the equation $\mu_A{}^* = \frac{\mu_A}{\mu_X}$.

Step 4. Calculation of projection values: The ChI is used to obtain overall value for each projection denoted by $V_{p_{ij}}$ by aggregating assessments with respect to multiple criteria using Eq. 4.

$$V_{p_{ij}} = \sum_{u=1}^{U} \left(f_{p_{ij}}(x_u) - f_{p_{ij}}(x_{u-1}) \right) \mu_{A_u}{}^* \tag{4}$$

Step 5. Calculation of scenario values: Since scenarios are constructed by combining projections of different factors, scenario values are calculated by aggregating projection values obtained in the previous step. In aggregating the projection values, consistency, which serves as the most commonly employed criterion in scenario planning (Amer et al., 2013), is utilized as the weighting factor. The main assumption is that the consistency between projections determines the consistency of the scenario. In this study, only pair-wise consistency is considered to minimize the complexity that arises from including higher-level combinations (i.e. bundles of three or more projections). The proposed equation to obtain scenario values is given in Eq. 5.

$$SV_k = \sum_{\{p_{ij}, p_{yz}\} \in W} (V_{p_{ij}} + V_{p_{yz}})\, con_{p_{ij}p_{yz}} \tag{5}$$

where $con_{p_{ij}p_{yz}}$ is the consistency value for the projections p_{ij} and p_{yz} in scenario k, $S_k = [p_{1j}\ \ldots\ p_{Ij}]$, SV_k is the value of scenario k, $k = 1, \ldots, K$. W is the set of two-element subsets of the scenario k.

Step 6. Selection of a manageable number of scenarios: A small and manageable number of scenarios should be selected to simplify and improve the strategic planning process. Also, strategic planning should be based on effective and diverse scenarios to cover future developments. Thus, organizations can adequately prepare for the future and ensure their readiness to tackle upcoming challenges. A nonlinear programming model is developed to select a reasonable number of scenarios under several constraints. The aim is to maximize the total distance between the selected scenarios. A dissimilarity measure is defined to determine the distance between scenarios as given in Eq. 6 (Prasetyo & Purwarianti, 2014).

$$D_{kt} = \frac{|F| - m}{|F|} \tag{6}$$

where D_{kt} is the dissimilarity (i.e. distance) value between scenario k and scenario t, $|F|$ is the number of factors and m is the number of projections matching in scenario k and scenario t.

The model is formulated as follows:

Indices

k, t: Index for scenarios $(1, \dots, K)$

Parameters

SV_k: The value of scenario k

D_{kt}: The distance between scenario k and t

TH: Threshold value for scenario values

$MaxS$: The maximum number of scenarios to be selected

$MinD$: The minimum distance between scenarios to be selected

M: Big number

Decision Variables

$$S_k: \begin{cases} 1, if\ scenario\ k\ is\ selected \\ 0\ \ o/w \end{cases}$$

$$max \sum_{k}^{K-1} \sum_{t,t>k}^{K} D_{kt} S_k S_t \tag{7}$$

$$\sum_{k=1}^{K} S_k \leq MaxS \tag{8}$$

$$S_k = 1 \qquad k = argmax_{i=1,\dots,K} SV_i \tag{9}$$

$$TH - SV_k \leq M\,(1 - S_k) \qquad \forall k \tag{10}$$

$$D_{kt} \geq MinD\ S_k S_t \qquad \forall k, t \text{ ve k < t} \tag{11}$$

$$S_k \in \{0,1\} \qquad \forall k \tag{12}$$

The objective function (Eq. 7) aims to select a scenario set which has the maximum total distance between scenarios. The number of scenarios to be selected is limited by Eq. 8. Eq. 9 ensures that the scenario with the largest value is selected. Eq. 10 guarantees that scenarios are eliminated if their values are lower than the threshold value. Eq. 11 ensures that there is at least a specified distance between scenarios to be selected.

The model produces a scenario set which includes diverse scenarios being able to cover a wide range of possible future developments with relatively high scenario values based on several criteria.

4. Scenario Planning Application for Future Transport

Urban mobility needs are changing due to environmental, social, technological and economic factors. Climate change, technological advancements in electric and autonomous vehicles, shared mobility, and scarcity of energy resources necessitate a shift from conventional transportation that has not provided economical and sustainable solutions. In order to address these issues and satisfy residents' expectations, effective strategies must be developed. Especially, metropolitan cities face even more challenging problems including growing population, traffic congestion, air quality, parking, safety, noise pollution, accessibility and integration of transport modes. Moreover, the dynamic nature of these cities increases uncertainty, making it difficult to develop strategies. Therefore, a scenario planning study was performed to explore potential scenarios for 2035 that help to build a sustainable future transport plan for a metropolitan city and also show the applicability of the proposed approach.

According to experts' opinions and literature review, 12 factors and 29 projections in total that are expected to be highly effective in future transport were identified. The expert group consists of a team of 11 individuals comprising transportation analysts, academics, and public transport planners. The required information was obtained through interviews.

Factor and projections are given in Table 2. Three criteria were defined to assess projections, which are plausibility (c_1), sustainability (c_2), and adaptability (c_3). Plausibility measures the degree of being capable of happening. Sustainability quantifies (either in positive or negative way) the level of environmental and economic contribution to sustainability of the determined projections. Adaptability measures the ability to adjust and cope with changes, reflecting the system's capacity for adaptation.

Table 2
Factors and projections

Factors	Projections
Travel Behavior of the Majority (ft_1)	Public transport (p_{11}) Individual vehicles (p_{12}) Bike, scooter etc. (p_{13})
Car Ownership (ft_2)	Increasing (p_{21}) Current state (p_{22}) Decreasing (p_{23})
Work Style (ft_3)	Remote work (p_{31}) On-office (p_{32})
Environmental awareness (ft_4)	High (voluntary) (p_{41}) Medium (duty) (p_{42}) Low (p_{43})
Land Use (ft_5)	High urban centric jobs and housing (p_{51}) High urban centric jobs and housing more dispersed (p_{52}) High urban centric housing and jobs more dispersed (p_{53})
New technologies for decarbonisation (Autonomous, electric vehicles etc.) (ft_6)	Limited (p_{61}) Widespread (p_{62})
Regulations and policies (ft_7)	Strict regulations for reducing usage of fossil fuel vehicles (p_{71}) Current state (p_{72})
Road Allocation (ft_8)	Road Allocations for bikes, scooters and public transports (p_{81}) Current state (p_{82})
Security (violence, harassment etc.) (ft_9)	High concern over security threats (p_{91}) Low concern over security threats (p_{92})
Connectivity of Public Transport (ft_{10})	High in only central areas ($p_{10,1}$) High in urban areas and limited in rural areas ($p_{10,2}$) High in all areas ($p_{10,3}$)
Distribution of Wealth and Income (ft_{11})	Inequality gap increases ($p_{11,1}$) Inequality gap decreases ($p_{11,2}$)
Real Time Transportation Data (ft_{12})	Highly improved ($p_{12,1}$) Current state ($p_{12,2}$)

Projections were assessed w.r.t. three criteria given in Table 3, using the predefined scales. Plausibility and sustainability were assessed on a scale ranging from very low to very high within the interval of [0,100]. Adaptability, on the other hand, was evaluated on a scale ranging from very high to very low within the interval of [0, 100]. The scale is reverse because exploring low adaptable projections is significant for the organizations. We aim to determine plausible scenarios as well as critical scenarios in terms of sustainability and adaptability. Individual criterion weights were assessed using a scale ranging from 0 to 1. To reduce the complexity of the assessments, a rating scale (no interaction (0), very low (0.2), low (0.4), medium (0.6), high (0.8), very high (1)) was used for criteria interactions as given in Table 3. Joint criteria weights were calculated using these assessments by Eq. 3 for three criteria and they were normalized because $\mu_{C\,(123)}$ was not equal to 1. Criteria weights are given in Table 4.

Table 3
Criteria assessments

Criteria	Weights	Interactions	Assessments
Plausibility (μ_1)	0.40	Plausibility and Sustainability (μ_{12})	Medium (0.60)
Sustainability (μ_2)	0.50	Plausibility and Adaptability (μ_{13})	Low (0.40)
Adaptability (μ_3)	0.20	Sustainability and Adaptability (μ_{23})	Very Low (0.20)
		All three criteria (μ_{123})	High (0.80)

To clarify how to obtain joint criteria weights, the calculation of μ_{123} is given as $\mu_{123} = \max(0.4 + 0.72 + 0.8 * 0.4 * 0.72;\ 0.5 + 0.632 + 0.8 * 0.5 * 0.632; 0.2 + 1.02 + 0.8 * 0.2 * 1.02)$ = 1.3848.

Table 4
Revised criteria weights

Criteria (A)	**Weights** (μ_A)	**Normalized Weights** ($\mu_A{}^*$)
1	0.40	0.289
2	0.50	0.361
3	0.20	0.144
1, 2	1.020	0.737
1, 3	0.632	0.456
2, 3	0.720	0.520
1, 2, 3	1.3848	1.000

Projection values were calculated using *ChI* and fuzzy measures as shown in Eq.4. Assessments were aggregated to obtain a single overall value for each projection with respect to three criteria. The values are given in the last column of Table 5. As an example, the calculation for the projection "Public transport (p_{11})" is given as follows:

Since $f(x_3) < f(x_1) < f(x_2)$, $V_{p_{11}} = \sum_{u=1}^{3}\left(f_{p_{11}}(x_u) - f_{p_{11}}(x_{u-1})\right) \mu_{A_u}{}^* = f(x_3)\, \mu_{123}{}^* + \left(f(x_1) - f(x_3)\right) \mu_{12}{}^* + \left(f(x_2) - f(x_1)\right) \mu_2{}^*$. $V_{p_{11}} = 20 * 1 + (70 - 20) * 0.737 + (75 - 70) * 0.361 = 58.66$.

Table 5
Assessment and overall values of projections

Projections	**Plausibility**	**Significance**	**Adaptability**	**Overall Values**
Public transport (p_{11})	70	75	20	58.66
Individual vehicles (p_{12})	60	75	35	58.84
Bike, scooter etc. (p_{13})	55	60	25	48.92
Increasing (p_{21})	40	70	60	54.01
Current state (p_{22})	50	55	20	43.92
Decreasing (p_{23})	55	75	45	59.59
Remote work (p_{31})	50	45	40	45.13
On-office (p_{32})	50	45	40	45.13
High (voluntary) (p_{41})	40	65	30	46.40
Medium (duty) (p_{42})	55	60	40	52.86
Low (p_{43})	40	70	50	52.42
High urban centric jobs and housing (p_{51})	45	50	60	49.04
High urban centric jobs and housing more dispersed(p_{52})	50	45	30	42.50
High urban centric housing and jobs more dispersed(p_{53})	30	60	35	41.63
Limited (p_{61})	35	55	45	43.81
Widespread (p_{62})	50	55	45	50.49
Strict regulations for reducing usage of fossil fuel vehicles (p_{71})	60	75	40	60.16
Current state (p_{72})	40	65	30	46.40
Road Allocations for bikes, scooters and public transports (p_{81})	45	70	50	54.82
Current state (p_{82})	35	60	30	42.71
High concern over security threats (p_{91})	55	75	70	64.61
Low concern over security threats (p_{92})	35	60	30	42.71
High in only central areas ($p_{10,1}$)	30	55	25	37.71
High in urban areas and limited in rural areas ($p_{10,2}$)	45	60	30	46.47
High in all areas ($p_{10,3}$)	45	65	40	50.91
Inequality gap increases ($p_{11,1}$)	60	55	65	57.45
Inequality gap decreases ($p_{11,2}$)	40	75	30	50.01
Highly improved ($p_{12,1}$)	70	60	40	57.63
Current state ($p_{12,2}$)	40	45	50	43.32

Scenarios are quantified through the use of projection values. Initially, consistency values between projection pairs are needed. These values were assessed by experts on the scale [0, 1] as given in Table A1. Considering the factors and projections, a total of 31,104 scenarios were generated. A scenario value was calculated for each of these using the Eq. 5. The values of the entire set of scenarios were not provided due to the space limitation, yet an example calculation is provided for $S_1 = [l_{11}, l_{21}, l_{31}, l_{41}, l_{51}, l_{61}, l_{71}, l_{81}, l_{91}, l_{10,1}, l_{11,1}, l_{12,1}]$:

$SV_1 = \sum_{\{p_{ij}, p_{yz}\} \in W} (V_{p_{ij}} + V_{p_{yz}})\, con_{p_{ij}p_{yz}} = \Big((V_{p_{11}} + V_{p_{21}}) con_{p_{11}p_{21}} + (V_{p_{11}} + V_{p_{31}}) con_{p_{11}p_{31}} + (V_{p_{11}} + V_{p_{41}}) con_{p_{11}p_{41}} + \cdots + (V_{p_{51}} + V_{p_{61}}) con_{p_{51}p_{61}} + (V_{p_{51}} + V_{p_{71}}) con_{p_{51}p_{71}} + \cdots + (V_{p_{10,1}} + V_{p_{12,1}}) con_{p_{10,1}p_{12,1}} + (V_{p_{11,1}} + V_{p_{12,1}}) con_{p_{11,1}p_{12,1}} \Big) = \big((58.66 + 54.01) \times 0.1 + (58.66 + 45.13) \times 0.3 + (58.66 + 46.40) \times 0.8 + \cdots + (49.04 + 43.81) \times 0.4 + (49.04 + 60.16) \times 0.4 + \cdots + (37.71 + 57.63) \times 0.4 + (57.45 + 57.63) \times 0.4\big) = 3251.68$

where W $\left(\left\{\{p_{11}, p_{21}\}, \{p_{11}, p_{31}\}, \{p_{11}, p_{41}\}, \ldots, \{p_{81}, p_{12,1}\}, \ldots, \{p_{10,1}, p_{12,1}\}, \{p_{11,1}, p_{12,1}\}\right\}\right)$ includes all pairs in Scenario 1.

Upon completion of the entire process, every scenario has a numerical value which makes them comparable. This is essential to have the ability to choose a number of influential scenarios in the future in order to take the necessary actions and precautions at present. In addition, selected scenarios should be different from each other to cover a wide range of future developments. Dissimilarity was used to measure the distance between all scenario pairs. For example, distance between $S_1 = [l_{11}, l_{21}, l_{31}, l_{41}, l_{51}, l_{61}, l_{71}, l_{81}, l_{91}, l_{10,1}, l_{11,1}, l_{12,1}]$ and $S_2 = [l_{11}, l_{21}, l_{31}, l_{41}, l_{51}, l_{61}, l_{71}, l_{81}, l_{91}, l_{10,1}, l_{11,1}, l_{12,2}]$ is $\frac{1}{12}$, since 11 projections are matched. All distances were calculated using Eq. 6 and considered as a parameter in the mathematical model. Scenario values were also represented as a parameter in the model. The experts established the remaining parameters as follows: the maximum number of scenarios (*MaxS*) was set at 4, the minimum distance between scenarios (*MinD*) was set at 0.55, and the threshold value (*TH*) was set at 3500, which falls between the third quartile and the maximum scenario value. The mathematical model was solved using Gurobi 9.5 with Python 3.8. The selected scenarios are given in Table 6.

Table 6
Selected scenarios

Factors	Scenario 4326 (Responsible Development)	Scenario 7415 (Efficient and Green)	Scenario 13183 (Individualist)	Scenario 13322 (Chaotic)
Travel behavior of the majority	Public transport	Public transport	Individual vehicles	Individual vehicles
Car ownership	Current state	Decreasing	Increasing	Increasing
Work Style	Remote work	Remote work	On-office	On-office
Environmental awareness	Medium (duty)	High (voluntarily)	Medium (duty)	Low
Land Use	High urban centric jobs and housing more dispersed	High urban centric housing and jobs more dispersed	High urban centric housing and jobs more dispersed	High urban centric jobs and housing
New technologies for decarbonisation	Widespread	Widespread	Widespread	Limited
Regulations and policies	Strict regulations for reducing usage of fossil fuel vehicles	Strict regulations for reducing usage of fossil fuel vehicles	Strict regulations for reducing usage of fossil fuel vehicles	Current state
Road allocation	Road allocations for bikes, scooters and public transports	Road allocations for bikes, scooters and public transports	Current state	Current state
Security	High concern over security threats	Low concern over security threats	High concern over security threats	High concern over security threats
Connectivity of public transport	High in urban areas and limited in rural areas	High in all areas	High in urban areas and limited in rural areas	High in only central areas
Distribution of wealth and income	inequality gap increases	inequality gap decreases	inequality gap decreases	inequality gap increases
Real time transportation data	Current state	Highly improved	Highly improved	Current state

The most prominent scenarios emerged as “Responsible Development”, “Efficient and Green”, “Individualist” and “Chaotic”. Responsible Development: The usage of fossil fuel cars has been limited and eco-friendly vehicles have increased. After the pandemic, the work style will significantly change. Although public transport is the major transportation mean, people will continue to use their own vehicles. According to the scenario "Efficient and Green", people’s environmental awareness will increase. They will prefer public transportation rather than individual vehicles, because public transport will become widespread not only in urban areas but also in rural areas. Technology will be adapted to both vehicles and urban transport systems. Security problems will be solved. According to the scenario "Individualist", regulations will be employed for fossil fuel cars. Environmental awareness will increase. However, car ownership will increase since there will be several problems such as security and road allocations. People will prefer individual vehicles due to the lack of necessary precautions to improve the urban transport system. According to the scenario "Chaotic", people will be unwilling to embrace new technologies and consider environmental impacts, resulting in a failure to implement essential measures for enhancing the urban transport system. Thus, people will turn to more individualistic options. These scenarios examined by area experts were found to be relevant and applicable.

The selected scenarios contain several opportunities and barriers. For example, with the increase in environmental awareness, the interest in public transportation has increased and car ownership has decreased or with the increase in individualism, car ownership and individual transport modes have increased. Actions should be taken for future developments which are seen as a barrier like high security concerns. According to the selected scenarios, strategies for decarbonization of public transport system, feeder routes of different transport modes, traffic calming, integration of transfers, and technology usage in network management control centers can be developed. For example, parking regulations, congestion charging and neighborhood mobility centers can be established for the individualist scenario. The scenarios also show projections which can co-exist and are affected from each other. Specific projects can also be developed considering these projections.

5. Conclusion

In this paper, a novel scenario planning approach is proposed for the evaluation and selection of scenarios. The approach provides a systematic framework for the whole process beginning with scenario development and ending with a manageable number of scenario selection. The advantage of the method is that it takes into account multiple criteria and the interaction between them, and also provides the selection of distinct scenarios representing the future space. The four scenarios that have been obtained reveal a valuable chance to identify potential opportunities, threats and challenges that may arise regarding future urban mobility systems. This in turn facilitates the development of a long-term planning for building a sustainable and people oriented system. Also, strategic planners can make informed decisions regarding which strategies are most likely to be effective and sustainable in the long run by analyzing these scenarios and associated outcomes.

The study has some limitations that should be noted. Determining interactions among criteria may be complex as the number of criteria increases. For scenario planning, since there are not many criteria, the approach is useful and straightforward. However, it could be difficult to assess interactions for experts in some problems such as multi criteria decision making problems. Different methods or approaches can be developed when the criteria exceed five. Consistency is another limitation because only projection pairs are taken into account. For the joint occurrences of more than two projections, learning based methods can be utilized to extract from existing data.

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Appendix

Table A1
Consistency Assessments

Projections	No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
p_{11}	1	0	0	0	0.1	0.3	0.9	0.3	0.7	0.8	0.7	0.4	0.4	0.6	0.6	0.5	0.7	0.4	0.4	0.5	0.3	0.3	0.7	0.4	0.5	0.8	0.6	0.8	0.8	0.4
p_{12}	2	0	0	0	0.8	0.5	0.1	0.3	0.6	0.1	0.2	0.7	0.4	0.3	0.6	0.6	0.3	0.4	0.6	0.4	0.6	0.8	0.4	0.5	0.5	0.4	0.7	0.4	0.4	0.5
p_{13}	3	0	0	0	0.1	0.4	0.6	0.3	0.4	0.7	0.6	0.2	0.6	0.5	0.2	0.3	0.5	0.4	0.4	0.7	0.4	0.3	0.6	0.4	0.4	0.6	0.4	0.4	0.7	0.5
p_{21}	4				0	0	0	0.2	0.7	0.1	0.2	0.6	0.2	0.7	0.7	0.5	0.6	0.4	0.5	0.3	0.5	0.9	0.2	0.7	0.6	0.3	0.8	0.3	0.3	0.5
p_{22}	5				0	0	0	0.5	0.5	0.3	0.4	0.4	0.5	0.7	0.6	0.5	0.6	0.5	0.9	0.5	0.8	0.5	0.4	0.6	0.6	0.4	0.6	0.4	0.4	0.6
p_{23}	6				0	0	0	0.8	0.3	0.8	0.6	0.3	0.4	0.4	0.3	0.5	0.7	0.6	0.5	0.7	0.1	0.1	0.7	0.2	0.4	0.8	0.3	0.7	0.6	0.3
p_{31}	7							0	0	0.5	0.5	0.5	0.4	0.8	0.7	0.5	0.4	0.5	0.4	0.6	0.4	0.3	0.6	0.7	0.5	0.3	0.7	0.4	0.4	0.6
p_{32}	8							0	0	0.5	0.5	0.5	0.6	0.3	0.5	0.4	0.5	0.4	0.5	0.4	0.6	0.5	0.4	0.5	0.5	0.5	0.3	0.6	0.6	0.4
p_{41}	9									0	0	0	0.3	0.4	0.7	0.2	0.7	0.8	0.3	0.8	0.1	0.4	0.4	0.2	0.4	0.7	0.4	0.5	0.5	0.5
p_{42}	10									0	0	0	0.4	0.4	0.6	0.3	0.7	0.7	0.4	0.6	0.3	0.4	0.4	0.2	0.4	0.7	0.4	0.5	0.5	0.5
p_{43}	11									0	0	0	0.6	0.6	0.6	0.5	0.4	0.4	0.4	0.5	0.5	0.4	0.4	0.2	0.4	0.7	0.4	0.4	0.5	0.5
p_{51}	12												0	0	0	0.4	0.4	0.4	0.6	0.7	0.2	0.4	0.3	0.8	0.7	0.2	0.5	0.5	0.3	0.6
p_{52}	13												0	0	0	0.4	0.4	0.2	0.5	0.5	0.6	0.3	0.3	0.2	0.6	0.7	0.7	0.4	0.7	0.4
p_{53}	14												0	0	0	0.4	0.4	0.7	0.4	0.8	0.4	0.2	0.5	0.2	0.5	0.8	0.2	0.7	0.7	0.4
p_{61}	15															0	0	0.2	0.6	0.3	0.8	0.4	0.4	0.4	0.4	0.4	0.5	0.4	0.4	0.4
p_{62}	16															0	0	1	0.2	0.7	0.4	0.4	0.4	0.4	0.5	0.6	0.3	0.6	0.4	0.4
p_{71}	17																	0	0	0.7	0.2	0.4	0.4	0.4	0.4	0.4	0.4	0.7	0.5	0.5
p_{72}	18																	0	0	0.4	0.8	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5
p_{81}	19																			0	0	0.2	0.7	0.4	0.5	0.6	0.4	0.4	0.8	0.5
p_{82}	20																			0	0	0.5	0.4	0.5	0.7	0.2	0.4	0.4	0.5	0.6
p_{91}	21																					0	0	0.4	0.7	0.2	0.9	0.2	0.5	0.6
p_{92}	22																					0	0	0.4	0.3	0.6	0.2	0.9	0.7	0.4
$p_{10,1}$	23																							0	0	0	0.7	0.2	0.4	0.5
$p_{10,2}$	24																							0	0	0	0.5	0.5	0.5	0.7
$p_{10,3}$	25																							0	0	0	0.2	0.8	0.8	0.3
$p_{11,1}$	26																										0	0	0.4	0.6
$p_{11,2}$	27																										0	0	0.7	0.4
$p_{12,1}$	28																												0	0
$p_{12,2}$	29																												0	0