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Synthesis of strategies in post-COVID-19 public sector supply chains under an intuitionistic fuzzy environment

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\textbf{ABSTRACT}

Entities in public sector supply chains (SCs) often operate independently despite having interdependent objectives. Such a fragmented operational design poses several problems magnified by the presence of necessary public health measures fueled by COVID-19. This work contributes to the domain literature by introducing an overarching framework for synthesizing strategies in public sector SCs. The underlying component is the translation of information from the upstream to the downstream entities of the SCs, which is carried out by a Kano-enhanced quality function deployment. The proposed framework introduces intuitionistic fuzzy (IF) decision maps with the aid of the full consistency method to incorporate inherent interrelationships among strategies in the translation agenda. Under an IF environment that better captures judgment uncertainties, an actual case study of a multi-level public sector SC motivated by a government-funded project under the COVID-19 pandemic is demonstrated in this work. Findings of the case suggest that the government prioritizes meeting all project objectives. This requirement is reflected in the downstream SC. The project planning entity focuses on creating an overarching plan of operations, material request entity on complying with government procurement protocols, and maintaining public health and safety in operations for the procurement entity. Results show the effective synthesis of strategies across the SC, ensuring SC integration and collaboration. The case study demonstrates that maintaining public health and safety is a significant component of post-COVID-19 public sector SCs. Several practical insights on the synthesis of public sector SC strategies are also provided in this work.

1. Introduction

The management of existing supply chains (SCs) has become a prevalent topic due to its strategic importance for organizations in gaining competitive advantage [1]. One driving force of its prominence is disruptive events that disrupt the material and resource flow. Most of these disruptions are caused by a natural disaster, supplier bankruptcy, war, and terrorism [2,3]. The disruption of the SC may have a cascading effect on relevant sectors, which may result in severe and devastating impacts [4]. Due to the adverse effects of SC disruption, mitigation actions become crucial. For instance Ref. [5], take on big data analytics to build an institutional response to SC disruptive events and establish IT infrastructure capabilities. Furthermore [6,7], developed a mathematical model to help address arising concerns for sustainable SC. The model involves several aspects of the production-distribution-inventory-allocation-location domain. On the other hand, Sawik [8] presented an integrated portfolio approach on supplier selection that efficiently considers the decisions made before and after the SC disruption. It is demonstrated in the literature that mitigating the impact of inevitable SC disruptions is possible with the comprehensive knowledge of the factors that affect the propagation of these disruptions [9]. This approach, however, may fall short when dealing with disruptions of

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multiple SCs, such as a global pandemic [10], emphasized that disruption of an upstream SC may lead to ripple effects downstream, which may cause the entire SC to shut down. This is accurately depicted in the recent disruption on the global SC caused by the COVID-19 pandemic [11], and multiple intelligent actors (e.g., government, organizations), each is satisfying their utilities, must be involved in the analysis (e.g., Ref. [12]).

When China decided to impose movement restrictions towards people and resources and cross-border restrictions to contain the spread of the coronavirus in January 2020, the global SC suffered a significant delay in material movement, which has been associated with the failure of raw material acquisition to support operations of many manufacturers worldwide that are dependent on the factories in China [13]. As a result, the global SC failed to promptly distribute the necessary goods to the public (i.e., toilet paper, cotton swab, wheat, and flour) [14]. In addition, the general population contributed to enormous variability in demand for specific goods when they resorted to panic buying and stockpiling in fear of resource shortage [13]. However [14], emphasized that the COVID-19 pandemic was not an aberration. Businesses are not entirely blindsided since the global SC has already been disrupted by major natural calamities, such as the 2003 SARS crisis and the Fukushima Daichi nuclear disaster [15]. Due to effective mitigation efforts, several businesses have successfully recovered their operations amid the pandemic. For instance, a pharmaceutical company presented in the study of [14] has been contracting with fourth-party logistics to find multiple available logistics options instead of a single-source logistics provider to develop an agile and resilient SC. Also, some companies voluntarily decided to pivot their normal operations into the procurement and manufacturing of essential supplies (i.e., personal protective equipment and ventilators) during the pandemic [16,17].

Since SC risks are multifaceted and unique to each case [18], businesses are still challenged to adapt existing mitigations for specific disruptions. Thus, despite the popularity of SC mitigation strategies for natural calamities, the scope of COVID-19 pandemic impact (i.e., number of affected people, geographical impact, and longevity of the situation) is inevitable to cause downstream interruption and closure of production in many SCs. Business operations for Apple, for instance, has been widely interrupted because their assembler, Foxconn, is working below capacity [19] due to the delay in material flow from Apple’s suppliers in China, Malaysia, South Korea, and Europe caused by the imposed lockdowns and a paucity of parts supplies from their sub-suppliers [20]. Evidently, there are constraints under the new normal conditions experienced by industries that adversely affect normal operations. Several companies were forced to adopt new ways of remotely working, utilizing new communication systems, altering work practices to meet social distancing protocols, and modifying work patterns to continue business operations [21]. On the other hand, Kodamo [22] also observed that public service organizations and governments are adapting through the utilization and deployment of technology applications and cloud-based infrastructure to provide services to their stakeholders.

In the public sector, supply chain management (SCM) may be interpreted as the acquisition of commodities and services by the government or public entities (e.g., through buying or purchasing) [23]. Public sector SCM is part of various economic activities that support government service delivery, social and political roles, ranging from simple goods to extensive construction and development projects [24]. To enhance transparency and accountability for all government activities, an organization assigned to control material acquisition (e.g., Bids and Awards Committee) is tasked to engage in the SC for the public sector, thus adding to the public sector SC’s complexity. Public sector SCM is deemed to have an essential role in the development of society due to its contribution to both micro- and macro-economic development [25]. Public procurement represents an average of 13%–20% of the GDP, and managing such activities boosts economic growth and shared prosperity [26]. However, the domain of public SC remains largely underexplored [27]. Nevertheless, ineffective public sector SCM can have adverse consequences for any economy [28]. Mismanaged public SC may result in excessive prices charged by suppliers, unreliable and substandard quality of goods and services, corruption, and waste [29].

The COVID-19 pandemic disrupted the usual face-to-face communication among entities of the public sector SC. This disruption adversely impacts the flow of information across the SC, which leads to misalignment of objectives, operational asynchrony, and dissatisfaction [30]; resulting in distortion, dilution, and diversion of sector financing, resources, and capacity [31]. These communication challenges are more pronounced in technologically deficient third-world countries. For instance, in the Philippines, the expiration of at least Php 9 billion (i.e., governmental departments) in addressing the COVID-19 pandemic became a highlight. This has amplified the health crisis in the country, especially since the wages of several contractual health workers are sourced from expired funds [31]. Emphasized that promoting an integrated plan would forge opportunities for greater sectoral integration. Such an agenda becomes relevant as decision-makers in the public sector face procedural, legal, and political constraints that might hamper integration efforts. In addition, many internal and external stakeholders, both in upstream and downstream SC, have conflicting goals, given the presence of public and private entities. Such integration of factors (initiatives and requirements) and actors (internal and external stakeholders) are crucial in public sector SCM. Thus, a framework to facilitate the synthesis of SC initiatives in the public sector amid the COVID-19 pandemic can be a useful tool to synchronize SC entities, promote proactive policy and plan development, and address the problems highlighted here. Despite such an important agenda, limited attention is offered in the current literature.

This work overcomes this gap by offering an integrated framework that synthesizes the strategies of SC entities in the delivery of public goods operating under response measures due to the pandemic. Such a synthesis requires that downstream entities of the public sector SC satisfy the requirements of those in the upstream. These links are initialized by a set of requirements identified by the government (i.e., as the implementing entity of public services) for a given project. In this work, the translation of requirements from the government to downstream entities of the public sector SC is facilitated with the use of the quality function deployment (QFD). QFD was initially designed as a product development tool for maximizing customer satisfaction by translating customer requirements into design decisions throughout the product or service development stages [32]. The core of the QFD is the house of quality (HoQ) that guides the design teams at every stage of product development to ensure that the product or service closely matches customer requirements [33]. However, analogous to analyzing markets, satisfying the requirements of each SC entity (i.e., government, downstream entities) is not linear, and to address this non-linear relationship, different customer satisfaction models (e.g., quadrilateral, Kano, analytic, American customer satisfaction indices) have been developed. Among these models, the Kano model is widely popular. It poses that the relation between the degree of satisfaction of the specific product or service features is dependent on the attribute under consideration and is not necessarily linear [34]. Since its development in 1984, its application has gained prominence in various domains of the literature, such as in healthcare (e.g. Ref. [35], smart manufacturing systems [36], logistics [37], education [38,39], among others. The role of the Kano is generally to elucidate the underlying feature of a given requirement that is used to interpret the QFD.

Analogous to the systematic transfer of quality from the product planning to production and assembly stage [40], the integration of the Kano model and the QFD (i.e., popularly coined as the Kano-QFD model) augments the translation of requirements of the entities from upstream to downstream public sector SC. However, these requirements have intertwined relationships not addressed in most Kano-QFD integration. These interrelationships, through dependence and feedback, would potentially alter the decisions. In addition, the evaluation of these
requirements at every level of the SC is associated with ambiguity and uncertainty brought about by the insufficient knowledge of the SC entities or the conditions of the decision-making environment. Thus, this work offers a systematic approach that extends the Kano-QFD model in handling dependence and feedback of the translation of the requirements of the SC entities. This approach resembles the fuzzy decision-making trial and evaluation laboratory (DEMATEL), analytic hierarchy process (AHP), and the analytic network process (ANP) integration of [41,42]. However, methodologically, we introduce innovations of the previous approach to advance some drastic drawbacks of its computational structure. First, the limitations of the fuzzy set theory of [43] in better handling uncertainty are addressed using the intuitionistic fuzzy set (IFS) theory introduced by Atanassov (1986). Secondly, the use of the full consistency method (FUCOM) [44] overcomes the burden necessary in eliciting judgments within the AHP. Finally, Yu and Tzeng [45] demonstrated the drawbacks of the DEMATEL-ANP, and fuzzy decision maps (FDM) are deemed beneficial to advance these drawbacks. Thus, this work contributes to the domain literature by exploring the preliminaries of the IFS, Kano-QFD integration, FUCOM, and the FDM. Section 2 presents the proposed framework, while Section 3 presents the case application. It proceeds with a discussion of findings in Section 5 and managerial insights in Section 6. It ends with a conclusion and discussion of future works in Section 7.

2. Preliminaries

2.1. Intuitionistic fuzzy set (IFS) theory

[43] proposed the fuzzy set theory (FST) in handling vagueness and uncertainty in computing information. An extension of the FST is the intuitionistic fuzzy set (IFS) theory introduced by Atanassov (1986). IFS is characterized by a membership function, a non-membership function, and a hesitancy degree that respectively express support, opposition, and neutrality in eliciting opinion. Atanassov (1986). This is an advantage over the FST as it can better handle the uncertainty of information, particularly within the framework of decision-making [46]. Detailed three main advantages of the IFS theory under a decision-making environment. First, it offers the ability to model unknown information via the degree of hesitation. In the practical application (e.g., COVID-19 pandemic), where decision-makers are unsure about their preferences, the IFS theory is more suitable in extracting opinion than the FST. Secondly, it is characterized by three grades of information that can better capture uncertainty comprehensively. Finally, the traditional FST only handles the degree of “agreement” but fails to represent the degree of “disagreement”, often depicted in eliciting opinion.

The following provides some fundamental concepts of the IFS relevant in this work.

**Definition 1.** (Atanassov, 1986): Suppose X is a finite, non-empty set. Then an IFS A in X is defined as

\[ A = \{x, \mu_A(x), \nu_A(x) : x \in X\} \]  \hspace{1cm} (1)

where \( \mu_A(x) : X \rightarrow [0,1] \) and \( \nu_A(x) : X \rightarrow [0,1] \) such that \( 0 \leq \mu_A(x) + \nu_A(x) \leq 1 \) \( x \in X \) (i.e., the intuitionistic condition), \( \mu_A(x) \) and \( \nu_A(x) \) represent the membership function and the non-membership function, respectively, of \( x \in X \) to \( A \). \( \pi_A(x) \) expresses the degree of lack of knowledge of every \( x \in X \) to \( A \), and \( 0 \leq \pi_A(x) \leq 1 \). \( \mu_A(x), \nu_A(x) \), and \( \pi_A(x) \) follow Equation (10)

\[ \pi_A(x) = 1 - \mu_A(x) - \nu_A(x), x \in X \]  \hspace{1cm} (2)

\( \pi_A(x) \) is also referred to as the intuitionistic index of \( x \) in \( A \), which is associated with the degree of indeterminacy membership of \( x \) in \( A \).

**Definition 2.** [47]: For any two intuitionistic fuzzy sets (IFSs) \( A = \{x, \mu_A(x), \nu_A(x) : x \in X\} \) and \( B = \{x, \mu_B(x), \nu_B(x) : x \in X\} \), the following operations hold,

\[ A \leq B \text{ if and only if } \forall x \in X, \mu_A(x) \leq \mu_B(x), \text{ and } \nu_A(x) \geq \nu_B(x) \]  \hspace{1cm} (3)

\[ A = B \text{ if and only if } A \leq B \text{ and } B \leq A \]  \hspace{1cm} (4)

\[ A \cup B = \{x, \max(\mu_A(x), \mu_B(x)), \min(\nu_A(x), \nu_B(x)) : x \in X\} \]  \hspace{1cm} (5)

\[ A \cap B = \{x, \min(\mu_A(x), \mu_B(x)), \max(\nu_A(x), \nu_B(x)) : x \in X\} \]  \hspace{1cm} (6)

Early works on IFS theory demonstrated its use within the agenda of multi-criteria (or attribute) decision-making [e.g., Refs. [48–51]]. A widely engaged research stream in IFS theory since its inception until lately is the notion of distance between two IFSs [52–55]. Some widely regarded distances includeHamming distance, normalized Hamming distance, Euclidean distance, normalized Euclidean distance, and Minkowski distance [52,54,59]. Here, we present the definition of the Euclidean distance offered by Ref. [56]. For convenience, we write an IFS as \( A = \{x, \mu_A(x), \nu_A(x)\} \). As \( A \), with \( \mu_A, \nu_A \in [0,1] \), \( 0 \leq \mu_A + \nu_A \leq 1 \).

**Definition 3.** [56]: Let \( A = (\mu_A, \nu_A) \) and \( B = (\mu_B, \nu_B) \) be any two IFSs. The Euclidean distance between the IFS \( A \) and \( B \), denoted by \( d_E(A, B) \), is defined as:

\[ d_E(A, B) = \sqrt{(\mu_A - \mu_B)^2 + (\nu_A - \nu_B)^2} \]  \hspace{1cm} (7)

When used in decision-making, a ranking of IFS becomes a crucial aspect. In this regard, significant interests from domain scholars are observable, and various approaches have been offered, where most of them were based on specific distance measures. The earliest and widely known approach, which is based on vague sets, was the score function of [57]. Due to its limitations [50], proposed an algorithm that combines the score function and the accuracy function of [58] in ranking IFS. Since then, several formulations have been put forward (e.g., Refs. [52,54,59]). Here, we present the notion of [54] on the ideal positive degree, which is based on Euclidean distance. The ideal positive degree intends to address some problems of inadmissibility, non-robustness problem, and indifference.

**Definition 4.** [54]: Let \( A = (\mu_A, \nu_A) \) be an IFS. The ideal positive degree \( I(A) \) of IFS \( A \) is described as follows:

\[ I(A) = 1 - \sqrt{\frac{(1 - \mu_A)^2 + (\nu_A)^2}{2}} \]  \hspace{1cm} (8)

**Theorem 1.** [54]: Let \( A = (\mu_A, \nu_A) \) and \( B = (\mu_B, \nu_B) \) be any two IFSs. It follows that \( A \geq B \) if and only if \( I(A) \geq I(B) \).

**Definition 5.** [47]: Let \( A = (\mu_A, \nu_A) \) and \( B = (\mu_B, \nu_B) \) be any two IFSs and a real number \( r > 0 \). Some operations are defined as follows:

(i) The complement of \( A \) denoted by \( A^c = (\nu_A, \mu_A) \) \hspace{1cm} (9)

(ii) \( A \oplus B = (1 - (1 - \mu_A)(1 - \mu_B), \nu_A \nu_B) \) \hspace{1cm} (10)

(iii) \( A \odot B = (\mu_A \mu_B, 1 - (1 - \nu_A)(1 - \nu_B)) \) \hspace{1cm} (11)

(iv) \( rA = (1 - (1 - \mu_A)^r, (\nu_A)^r) \) \hspace{1cm} (12)
A) \( A' = (\mu_A', 1 - (1 - \mu_A')) \) \( (13) \)

Another flourishing area of IFS theory lies in the aggregation operators of IFSs. Early works highlight some arithmetic aggregation operators \[60\] and geometric aggregation operators \[61\]. Based on these methods \[62\], offered the notion of generalized aggregation operators \[63\], discussed some aspects and areas of IFSs and offered a mechanism to defuzzify an IFS.

**Definition 6.** \[60\]: Let \( A_j = (\mu_{A_j}, \nu_{A_j}) (j = 1, 2, \ldots, n) \) be a collection of IFSs. Then the intuitionistic fuzzy weighted averaging (IFWA) operator of \( A_j \) is defined as follows
\[
\text{IFWA}(A_1, A_2, \ldots, A_n) = \left( \frac{\sum_{j=1}^{n} w_j A_j}{\sum_{j=1}^{n} w_j} \right)
\] \( (14) \)

where \( w_j \ (j = 1, \ldots, n) \) is the weight vector of \( A_j = (\mu_{A_j}, \nu_{A_j}) \), with \( w_j \in [0, 1] \) and \( \sum_{j=1}^{n} w_j = 1 \). For \( w_j = \frac{1}{n} (j = 1, \ldots, n) \), the IFWA operator is reduced to an intuitionistic fuzzy averaging (IFA) operator of \( n \) dimension, defined as:
\[
\text{IFWA}(A_1, A_2, \ldots, A_n) = \frac{1}{n} (A_1 \oplus A_2 \oplus \ldots \oplus A_n)
\] \( (15) \)

The notion of an intuitionistic fuzzy number (IFN), as a special type of IFS, was put forward by Ref. \[64\] while drawing an analogy from vague sets. Some notes on IFNs were offered by Refs. \[65,66\].

**Definition 7.** \[64\]: An intuitionistic fuzzy number (IFN) \( A \) is characterized by the following properties:

(i) an intuitionistic fuzzy subset on the real number line
(ii) normal, i.e., there exists \( x_0 \in \mathbb{R} \) such that \( \mu_A(x_0) = 1 \), which implies that \( \nu_A(x_0) = 0 \).
(iii) convex for the membership function \( \mu_A \), i.e.,
\[
\mu_A(\lambda x_1 + (1-\lambda) x_2) \geq \min\{\mu_A(x_1), \mu_A(x_2)\}, \forall x_1, x_2 \in \mathbb{R}, \lambda \in [0, 1]
\]
(iv) concave for the non-membership function \( \nu_A \), i.e.,
\[
\nu_A(\lambda x_1 + (1-\lambda) x_2) \leq \max\{\nu_A(x_1), \nu_A(x_2)\}, \forall x_1, x_2 \in \mathbb{R}, \lambda \in [0, 1]
\]

A “generalized” notion of the IFN was proposed by Ref. \[67\]. As a special type of IFN, the triangular intuitionistic fuzzy number (TIFN) is defined as follows:

**Definition 8.** \[56\]: A TIFN \( \tilde{a} = (a_1, a_2, a_3) \): \( w^* = w^* \) is a special IFS on \( \mathbb{R} \), whose membership function \( \mu_{\tilde{a}} \) and the non-membership function \( \nu_{\tilde{a}} \) are defined as follows:
\[
\mu_{\tilde{a}}(x) = \begin{cases} 
(x - a_1)w_{\tilde{a}}/(a_2 - a_1) & \text{if } a_1 \leq x < a_2; \\
(a_3 - x)w_{\tilde{a}}/(a_3 - a_2) & \text{if } a_2 \leq x \leq a_3; \\
0 & \text{otherwise}
\end{cases}
\] \( (16) \)

\[
\nu_{\tilde{a}}(x) = \begin{cases} 
(a_2 - x + w^*_2x(a_3 - a_1))/(a_2 - a_1) & \text{if } a_1 \leq x < a_2; \\
(a_3 - x + w^*_3x(a_3 - a_2))/(a_3 - a_2) & \text{if } a_2 \leq x \leq a_3; \\
0 & \text{otherwise}
\end{cases}
\] \( (17) \)

where \( w_{\tilde{a}} \) and \( w^*_{\tilde{a}} \) represent the maximum membership degree and the minimum non-membership degree, respectively, such that \( w_{\tilde{a}} \leq w_{\tilde{a}}^* \leq 1 \). A TIFN \( \tilde{a} \) expresses an ill-known “approximate \( a_0^* \)”, which denotes a quantity approximately equal to \( a_2 \) \[68\]. Accordingly, the “approximate \( a_0^* \)” is expressed by way of any value in between \( a_1 \) and \( a_3 \) with varying degrees of membership and non-membership. It further implies that the most possible value is \( a_2 \) with a membership degree and non-membership degree of \( w_{\tilde{a}} \) and \( w^*_{\tilde{a}} \), respectively. On the other hand, both \( a_1 \) and \( a_3 \) have a membership degree of 0 and a non-membership degree of 1. Any \( x \in (0, 1) \) has a membership degree of \( \mu_{\tilde{a}}(x) \) and a non-membership degree of \( \nu_{\tilde{a}}(x) \). If \( w_{\tilde{a}} = 1 \) and \( w^*_{\tilde{a}} = 0 \), then \( \mu_{\tilde{a}}(x) + \nu_{\tilde{a}}(x) = 1 \) (\( \forall x \in \mathbb{R} \)). Consequently, the TIFN \( \tilde{a} = (a_1, a_2, a_3): w_{\tilde{a}}, w^*_{\tilde{a}} \) becomes \( \tilde{a} = (a_1, a_2, a_3): 1, 0 \), which essentially represents the triangular fuzzy number (TFN) in FST \[69\], making the TIFN a generalization of the TFN. The parameters \( w_{\tilde{a}} \) and \( w^*_{\tilde{a}} \) reflect the confidence and non-confidence level of the TIFN \( \tilde{a} \), which expresses more uncertainty than the triangular fuzzy number \[68\].

### 2.2. The Kano model, its intuitionistic fuzzy set extension, and the quality function deployment

[34] have developed a two-dimensional model to understand customer requirements (CRs) or attributes and their impact on customer satisfaction (CS). The Kano model divides CRs into six categories, each affecting CS differently. In Fig. 1, Kano categories are briefly explained as follows \[70–72\]:

- **Attractive (A):** The functional presence of these attributes will result in a high level of CS, while their absence will not affect CS.
- **One-dimensional (O):** The functional presence of these attributes will generate CS, while their absence will result in non-satisfaction.
- **Must-be (M):** Customers take the presence of these attributes for granted. Insufficiency of these attributes will result in extreme non-satisfaction, but the sufficiency will not increase satisfaction level.
- **Indifferent (I):** The attributes in this category, whether present or not, do not affect CS.
- **Reverse (R):** The presence of these attributes will generate non-satisfaction and vice versa.
- **Questionable (Q):** This outcome indicates that either the responses do not make any logical sense or the question was phrased incorrectly.

As shown in Table 1, the Kano model assigns two questions for each attribute, representing its functional and dysfunctional aspects, and a five-by-five evaluation table is generated to evaluate which category such an attribute belongs to Ref. \[34\].

The Kano model is widely used in analyzing CRs \[73\]. However, the traditional Kano model is a qualitative method that provides limited decision support for designers \[74–76\]. \[70\] initialized the quantitative analysis of the Kano model with two quantitative CS coefficients, namely, the satisfaction index and the dissatisfaction index, to reflect the average impact of a CR on customer satisfaction or dissatisfaction. Then, the CS coefficients have been modified and utilized as adjustment factors for re-prioritizing CRs to achieve maximum CS \[77,78\].

Recently, an IFS extension of the Kano model was introduced by Ref. \[79\]. The extension addresses the uncertainty and vagueness associated with how people express their preferences in the evaluation process. In their extension, they used TIFNs to represent the evaluation scores of decision-makers answering the functional and dysfunctional questions, i.e., Enjoy \( (7, 9, 9) \), Expect \( (5, 7, 9) \), Neutral \( (3, 5, 7) \), Live with \( (1, 3, 5) \), and Dislike \( (1, 1, 3) \), with membership and non-membership functions defined in Equation (16) and Equation (17), respectively. Then with an evaluation elicited by the decision-maker, membership function degrees are obtained. They devised a membership degree denoted by computing for
\[
\mu_{\tilde{a}}^{\mu} = m(F)^{\mu} \times m(D)^{\nu}_{\mu}
\] \( (18) \)

where \( m(F)^{\mu} \) and \( m(D)^{\nu}_{\mu} \) represent the membership and non-membership degrees of the \( i \) th standard answer to the functional
question (i.e., \( F_i \)) and \( j \)th standard answer to the dysfunctional question (i.e., \( D_j \)), elicited by the \( \eta \)th participant on the \( \kappa \)th CR as evaluated by the \( \theta \)th participant is shown in Equation (20) [79].

\[
V = [v_{ij}]_{5 \times 5} = \begin{bmatrix}
0 & 0.200 & 0.250 & 0.300 & 0.500 \\
-0.100 & 0 & 0.050 & 0.075 & 0.900 \\
-0.125 & -0.025 & 0 & 0.100 & 1.000 \\
-0.150 & -0.038 & -0.050 & 0 & 0.800 \\
-0.250 & -0.450 & -0.500 & -0.400 & 0 \\
\end{bmatrix}
\]

(19)

\[
AF^2 = \sum_{i=1}^{5} \sum_{j=1}^{5} v_{ij}^2
\]

(20)

The Kano model has long been integrated with QFD (see Refs. [77, 78]). QFD has long been the primary framework for product development. It is a technique used to translate the “voice of customers” into engineering design specifications while providing quality assurance throughout the production phase [80]. The majority of works on QFD-based product design focus on the first phase of QFD, highlighting the linking of customer requirements to product design needs, as illustrated in the HoQ in Fig. 2.

Customer needs and demands are found in Section A, usually based on market research. The computations for prioritizing Section A are found in Section B. The product they seek to design and develop is described in Section C. It is usually launched from Section A. The strength of the relationship between each element of Sections A and C is judged in Section D. Section E contains the Section C correlations. Finally, Section F prioritizes the design targets from Section C.

2.3. Full consistency method (FUCOM)

Like the well-known AHP [81] and the best-worst method (BWM) [82], the FUCOM was developed by Ref. [44] as comparison-based multi-attribute decision-making (MADM) method that combines some of the features of the AHP and the BWM in generating the priority weights of a set of pre-defined attributes (or criteria). Closely linked to the BWM, where the attribute weights are obtained via an optimization model constructed from two comparison systems based on best and worst attributes, FUCOM diverges from such construction by introducing two familiar groups of constraints: (1) consistency between the relations of attribute weights and the comparative priorities of these attributes, and (2) mathematical transitivity. The optimization model determines the allocation of priority weights of the attributes by minimizing the deviation from full consistency (DFC) metric, denoted by \( \chi \), associated with these two constraint groups. Such a metric measures the reliability of the resulting attribute weights. Compared to AHP and BWM, the major strength of the FUCOM is the minimal pairwise comparison that decision-makers need to perform, thereby minimizing their mental workload in the judgment elicitation process. When FUCOM is used to derive weights of the attributes (or criteria) as well as the priority weights of the alternatives for each attribute, then FUCOM can be used to solve a classic MADM problem under a goal-criteria-alternative hierarchical structure.

Usually integrated with other methods, the efficacy of the FUCOM has been demonstrated in decision-making problems related to supply chain management [83,84], sustainable supplier selection [85], human resource evaluation [86], service quality improvement [87], and business process management [88], among others. Here, the computational steps of the FUCOM are introduced following [44]. The term “criteria” is used here for representation. In general, they can be referred to as any set of homogeneous elements (e.g., attributes, factors).

\[
\text{Step 1}: \text{From the set of evaluation criteria } C = \{ c_1, c_2, \ldots, c_n \}, \text{ the criteria are ranked according to their degree of significance. According to the expected weights of the criteria, then the criteria set can be ranked as follows:}
\]

\[
c_{(1)} > c_{(2)} > \cdots > c_{(k)}
\]

(21)

where \( k \) indicates the rank of the observed criterion. If two criteria are perceived to have equal weights, then “\( > \)” can be replaced by “\( = \)”.

\[
\text{Step 2}: \text{The ranked criteria are compared, and the comparative priority } (P_{(k+1)}, k = 1, 2, \ldots, n), \text{ where } k \text{ represents the rank of the criterion in the set of evaluation criteria is determined. The vector of the comparative priorities of the criteria is represented as:}
\]
\[ \Phi = (\varphi_{1(1)}, \varphi_{2(1)}, \ldots, \varphi_{k(1)}) \]  

where \( \varphi_{k(1)} \) represents the priority that the criterion rank \( \chi_k \) has compared to the criterion \( \chi_{k+1} \) rank.

**Step 3:** The final weights \( (w_j : j = 1, \ldots, n)^T \) of the evaluation criteria are computed. These weight values should satisfy the following two conditions: (1) the ratio of the weight values is equal to the comparative priority among the observed criteria \( \varphi_{k(1)} \) defined in Step 2, i.e., the following condition is met:

\[
\frac{w_j}{w_{k+1}} = \varphi_{k(1)} \quad (23)
\]

(2) in addition, the final weight values should satisfy the transitivity requirement, i.e., \( \varphi_{k(1)} \otimes \varphi_{k(1)}(k-1) = \varphi_{k(1)}(k-2) \). Since \( \varphi_{k(1)} = \frac{w_j}{w_{k+1}} \) and \( \varphi_{k(1)}(k-1) = \frac{w_j}{w_{k+2}} \), that \( \frac{w_j}{w_{k+1}} \otimes \frac{w_j}{w_{k+2}} = \frac{w_j}{w_{k+2}} \). Thus, the following condition is required:

\[
\frac{w_j}{w_{k+2}} = \varphi_{k(1)}(k-1) \otimes \varphi_{k(1)}(k-2) \quad (24)
\]

To attain full consistency, these two conditions must be met. In meeting these conditions, the weight assignments \( (w_j : j = 1, \ldots, n)^T \) must satisfy \( \frac{w_j}{w_{k+1}} - \varphi_{k(1)}(k-1) \leq \chi \) and \( \frac{w_j}{w_{k+2}} - \varphi_{k(1)}(k-1) \otimes \varphi_{k(1)}(k-2) \leq \chi \), where \( \chi \) represents the DFC.

Thus, obtaining the weight vector \( (w_j : j = 1, \ldots, n)^T \) requires solving the following optimization problem:

\[
\min \chi
\]

subject to:

\[
\frac{w_j}{w_{k+1}} - \varphi_{k(1)}(k-1) \leq \chi, \forall k
\]

\[
\frac{w_j}{w_{k+2}} - \varphi_{k(1)}(k-1) \otimes \varphi_{k(1)}(k-2) \leq \chi, \forall k
\]

\[
\sum_{j=1}^{n} w_j = 1
\]

\[
w_j > 0, \forall j
\]

### 2.4. Fuzzy decision maps

The framework of fuzzy decision maps (FDMs) was first proposed by Ref. [45] to deal with a decision-making problem that assigns priority weights to elements with dependence and feedback. FDMs overcome the limitations of the AHP and the ANP in determining the overall priorities of decision elements that constitute a network. It combines the eigenvalue method of the AHP and the fuzzy graph-theoretic approach of fuzzy cognitive mapping (FCM). The AHP, developed by Ref. [81]; provides a process in determining the weights of elements within the same level of a decision hierarchy. On the other hand, the FCM originally introduced by Ref. [89] is an extension of cognitive maps [90] that incorporates fuzzy sets to depict fuzzy relationships among objects in a complex system. The basic notion of the FCM is as follows:

Given a 4-tuple \( (N, E, C, F) \) where \( N = \{1, 2, \ldots, n\} \) denotes a set of \( n \) elements or concepts, \( E = (e_{ij})_{n \times n} \) is an \( n \times n \) matrix where \( e_{ij} \in [-1, 1] \) represents the fuzzy causal relationship of an element \( i \) to element \( j \) (i.e., \( e_{ij} > 0, e_{ij} < 0, \) and \( e_{ij} = 0 \) denote positive, inverse, and no relationship, respectively), \( C \) is a state matrix where \( C^{(0)} \) represents the initial state and \( C^{(t)} \) signifies the state after \( t \) iterations, and \( f \) is the threshold function. The threshold function keeps the value of the concept in \( C^{(t)} \) within \([0, 1]\). Some popular threshold functions include the hard limit, hyperbolic tangent, and logistic functions. The influence of a specific element on another element at any given iteration is calculated using the updating equation as follows:

\[
C^{(t+1)} = f(C^{(t)} \cdot E), \quad C^{(0)} = I_{n \times n}
\]

The methodology of the fuzzy decision map can be outlined as follows:

Step 1: Compare the importance of the elements to determine their local priority vector \( \pi \) using the eigenvalue approach of the AHP.

Step 2: Determine the fuzzy cognitive map to reflect the fuzzy relationships among elements.

Step 3: Use Equation (26) to obtain the steady-state matrix \( C \).

Step 4: Normalize the local priority weight vector and the steady-state matrix using Equation (27) and Equation (28).

\[
z_{\text{norm}} = \frac{1}{\lambda} \pi
\]

where \( z_{\text{norm}} \) is the normalized local priority vector and \( \lambda \) is the largest eigenvalue of the matrix.
interrelationships among government requirements and among upstream entity strategies, the proposed model integrates them into the analysis. They are reflected in Section A and Section H, respectively. The causal relationships of requirements on strategies are reflected in Section I. The final priority weights of the upstream entity strategies are shown in Section J, which considers all information from Section A to Section I.

The modelling framework integrates the information (i.e., strategies, priorities) of the government and the initial information (i.e., strategies, priorities) of the upstream entity into a holistic approach in a way that an output reflects a synthesis represented by an “aggregate” priority of the upstream entity, under an environment that captures uncertainty in the decision-making process. The entity in the second level (e.g., SC entity 2) of the public sector SC realizes the information of the upstream entity (i.e., strategies, priorities) and takes this set of information in developing and prioritizing strategies. The same holistic platform is adopted to generate the “aggregate” information (i.e., final priority weights in Section J) for use in the downstream member. Such a process is repeated to all entities of the public sector SC represented in the system boundary of Fig. 3, except that the “government requirements” are replaced by previous SC entity strategies. The strategies of the previous SC entity (i.e., represented as a modified HoQ) in Section E become inputs to Section B of the next modified HoQ. Also, the final priority weights in Section J of the previous HoQ are inputs to Section C of the next HoQ. Through transitions among modified HoQs, this modelling framework assures integration and synthesis of information across the public sector SC.

The proposed algorithm that computes the final priority weights of SC entity strategies in Section J of each modified HoQ in Fig. 3 is as follows:

Step 1: As the project champion, the government identifies the requirements for a project that intends to deliver public goods [Section B].

Step 2: The government elicits judgments on the priorities of these requirements.

Due to the uncertainty associated with the judgment elicitation process, the IFS theory is integrated into the framework of FUCOM in generating priority weights of the requirements. It is noteworthy that this work offers the first attempt to incorporate IFS into FUCOM. After arranging these requirements in decreasing order of importance, the government elicits evaluation \( \phi_k = (\mu_{k,1}, \nu_{k,1}) \) which represents the intuitionistic fuzzy (IF) importance of the requirement with rank \( k \) over the requirement with rank \( k+1 \).

Step 3: Obtain the priority weights of the requirements [Section C].

In obtaining these weights, the IFS is integrated into the computational platform of FUCOM. This process requires solving two optimization problems in Equation (30) and Equation (31).

\[
\min_{\mu} \sum_{j=1}^{n} \nu_j \\
\text{subject to:} \\
\left| \frac{\mu_{k+1}}{\mu_{k+1}} - \frac{\mu_{k}}{\mu_{k}} \right| \leq \xi, \forall k \\
\left| \frac{\mu_{k+1}}{\mu_{k+1}} \otimes \frac{\mu_{k+1}}{\mu_{k+1}} \right| \leq \xi, \forall k \\
\mu_{k+1} \geq \mu_{k+1} \geq \cdots \geq \mu_{k+1} \\
\sum_{j=1}^{n} \mu_{j,1} = 1
\]
These optimization problems are analogous to the problems proposed by Ref. [96] in solving the IF extension of the BWM. Their approach suggests two optimization models corresponding to the membership and non-membership degrees of the TIFNs better captures the uncertainty of the evaluation process. Since Equation (25) is closely matched to the required optimization problem of the BWM in solving for the weights of the elements, then the IF-FUCOM integration can be developed accordingly. The proposed problems in Equation (30) and Equation (31) generate \( \tilde{w}_i = (\mu_{\tilde{w}_i}, \nu_{\tilde{w}_i}) \) which represents the IF priority weights of the government requirements defined by a membership degree \( \mu_{\tilde{w}_i} \) and non-membership degree \( \nu_{\tilde{w}_i} \).

### Step 4: The government elicits satisfaction degree of the functional and dysfunctional form of the requirements [Section D].

We modify the IFS-Kano integration of [79]. This process generates a 1–9 rating for each form of the requirement \((1, \ldots, n_1)\). Such an evaluation is mapped to the TIFNs \( \tilde{\alpha}_{\text{like}} = (7, 9, 9), \tilde{\alpha}_{\text{Must}} = (5, 7, 9), \tilde{\alpha}_{\text{Neutral}} = (3, 5, 7), \tilde{\alpha}_{\text{Live}} = (1, 3, 5), \) and \( \tilde{\alpha}_{\text{Dislike}} = (1, 1, 3) \), a slight variation of the linguistic terms in Ref. [79]. This mapping may produce one or more \( \rho \) and \( \sigma \) combinations, where \( \rho, \sigma \in \{\text{Like}, \text{Must} \text{ be}, \text{Neutral, Live with, Dislike}\} \). Each \( \rho, \sigma \) combination is represented by an IFS \( \tilde{A}_{ij} = (\mu_{\tilde{A}_{ij}}, \nu_{\tilde{A}_{ij}}) \) where \( \mu_{\tilde{A}_{ij}} \) and \( \nu_{\tilde{A}_{ij}} \) are computed using Equation (16) and Equation (17), respectively. With the Kano evaluation table proposed by Ref. [79] in Equation (19), the adjustment factor \( AF \) is as follows:

\[
AF = \left( \mu_{A_{ij}}, \nu_{A_{ij}} \right) = \sum_{j=1}^{n} \sum_{i=1}^{n} \lambda_j \tilde{A}_{ij} = \sum_{j=1}^{n} \sum_{i=1}^{n} \lambda_j \left( \mu_{\tilde{A}_{ij}}, \nu_{\tilde{A}_{ij}} \right)
\]

The operations in Equation (32) are defined in Equation (10) and Equation (12) of Definition 4. The aggregation in Equation (32) includes both membership and non-membership degrees of the TIFNs, as opposed to Ref. [79]; which merely uses the membership degrees. The inclusion of both membership and non-membership degrees of the TIFNs better captures the uncertainty of the evaluation process.

**Step 5: Aggregate the IF priority weight and the adjustment factor for each requirement.**

The adjustment factors \( AF \) obtained in Equation (32) are integrated into \( \tilde{w}_i = (\mu_{\tilde{w}_i}, \nu_{\tilde{w}_i}) \) which are computed as follows:

\[
\tilde{w}_i = \left( \mu_{\tilde{w}_i}, \nu_{\tilde{w}_i} \right) = AF \otimes \tilde{w}_i = \left( \mu_{AF \cdot \tilde{w}_i}, \nu_{AF \cdot \tilde{w}_i} \right) = \left( \mu_{\tilde{w}_i}, \nu_{\tilde{w}_i} \right)
\]
Step 6: The upstream entity identifies response strategies [Section E].

Given the list of requirements set by the government, the upstream entity (SC entity 1) identifies a set of specific strategies as a response to the requirements. These strategies are known via a consensus of the relevant stakeholders of the SC entity. They would take into account the current environmental conditions (e.g., public health crisis due to COVID-19).

Step 7: Perform Step 3 to Step 5 to generate the adjusted IF priority weights \( \tilde{w}_i \) (1, ..., \( n_2 \)) of the upstream entity strategies. This step generates [Section F] and [Section G] of Fig. 3.

The remaining steps intend to implement the IF extension of the FDM. It is again noteworthy that this work offers the first attempt to explore such an extension. The extension, referred here as the intuitionistic fuzzy decision map (IFDM), is structured analogously with the extension proposed by Ref. [92] by assigning TFNs \( \tilde{c}_j \in E \). Rather than obtaining the weights of the elements (i.e., stored in \( z \)) through the eigenvalue method of the AHP as in the original FDM formulation, the adjusted IF priority weights generated by Step 4 to Step 7 are used in the computation of the global priority weights.

Step 8: Build the IF decision map [Section A], [Section H], [Section I].

The elements in the IFDM consist of both the government requirements (\( i = 1, ..., n_1 \)) and the upstream entity strategies (\( i = 1, ..., n_2 \)). The upstream entity provides the IF weights of the fuzzy relationships among elements. The IF causal relationships of the elements are described in \( \tilde{E} = (\tilde{c}_{ij})_{n_1 \times n_2} = ((\tilde{c}_{ij}^{\nu}, \tilde{c}_{ij}^{\mu}))_{n_1 \times n_2} \). For better illustration, \( \tilde{E} \) is depicted in Fig. 4 as a partitioned matrix of IF causal relationships. Each partition of \( \tilde{E} \) describes a corresponding section of an HoQ in Fig. 3.

Step 9: Obtain the steady-state matrix.

The steady-state matrix \( \tilde{C}^* = (\tilde{c}_{ij}^{\nu}, \tilde{c}_{ij}^{\mu})_{n_1 \times n_2} \) is obtained using the updating Equation (34) and Equation (35). Note that each iteration \( t \) (\( t = 1, ..., \)) generates a matrix \( \tilde{C}^{(t)} = (\tilde{c}_{ij}^{\nu}, \tilde{c}_{ij}^{\mu}) \). Then we can obtain two matrices from \( \tilde{C}^{(t)} \) by introducing \( [\tilde{c}_{ij}^{\nu}]^{(t)} = [\tilde{c}_{ij}^{\nu}]^0 \) and \( [\tilde{c}_{ij}^{\mu}]^{(t)} = [\tilde{c}_{ij}^{\mu}]^0 \).

\[
\begin{align*}
[\tilde{c}_{ij}^{\nu}]^{(t+1)} &= f \left( [\tilde{c}_{ij}^{\nu}]^t, [\tilde{c}_{ij}^{\mu}]^t \right) \quad (34) \\
[\tilde{c}_{ij}^{\mu}]^{(t+1)} &= f \left( [\tilde{c}_{ij}^{\nu}]^t, [\tilde{c}_{ij}^{\mu}]^t \right) \quad (35)
\end{align*}
\]

where \( f \) represents the threshold function. This process is analogous to the TFN extension of the FDM proposed by Ref. [92].

Step 10: Normalize the steady-state matrix.

With the steady-state matrix \( \tilde{C}^* = (\tilde{c}_{ij}^{\nu}, \tilde{c}_{ij}^{\mu})_{n_1 \times n_2} \), we can write \( [\tilde{c}_{ij}^{\nu}] = [\mu_{\tilde{c}_{ij}^{\nu}}, \lambda_{\tilde{c}_{ij}^{\nu}}] \) and \( [\tilde{c}_{ij}^{\mu}] = [\mu_{\tilde{c}_{ij}^{\mu}}, \lambda_{\tilde{c}_{ij}^{\mu}}] \). The normalized matrices \( \tilde{C}' = (\mu_{\tilde{c}_{ij}^{\nu}}, \mu_{\tilde{c}_{ij}^{\mu}})_{n_1 \times n_2} \) can be represented as \( [\tilde{c}_{ij}^{\nu}] = [\mu_{\tilde{c}_{ij}^{\nu}}, \lambda_{\tilde{c}_{ij}^{\nu}}] \) and \( [\tilde{c}_{ij}^{\mu}] = [\mu_{\tilde{c}_{ij}^{\mu}}, \lambda_{\tilde{c}_{ij}^{\mu}}] \), where

\[
\begin{align*}
\mu_{\tilde{c}_{ij}^{\nu}} &= \frac{1}{\lambda_{\tilde{c}_{ij}^{\nu}}} \mu_{\tilde{c}_{ij}^{\nu}} \\
\mu_{\tilde{c}_{ij}^{\mu}} &= \frac{1}{\lambda_{\tilde{c}_{ij}^{\mu}}} \mu_{\tilde{c}_{ij}^{\mu}}
\end{align*}
\]

where \( \gamma_\nu = \max_i \sum_{j=1}^{n_1} \mu_{\tilde{c}_{ij}^{\nu}} \) and \( \gamma_\mu = \max_i \sum_{j=1}^{n_1} \mu_{\tilde{c}_{ij}^{\mu}} \).

Step 11: Normalize the adjusted IF weights.

Let \( N = \{1, ..., n\} = \{1, ..., n_1, 1, ..., n_2\} \) where \( n = n_1 + n_2 \), and \( \{1, ..., n_1\} \) represents the set of government requirements and \( \{1, ..., n_2\} \) is the list of upstream entity strategies. Thus, the adjusted IF weights of \( n \) elements can be written as \( \tilde{w}_i = (\mu_{\tilde{w}_i}, \nu_{\tilde{w}_i}) \). Analogous to Step 10, the vector \( \tilde{w}_i \) can be represented as \( [\tilde{w}_i^{\nu}] \) and \( [\tilde{w}_i^{\mu}] \). The normalized IF weight for each \( i \), denoted as \( \tilde{w}_i^{\mu} = (\mu_{\tilde{w}_i^{\nu}}, \nu_{\tilde{w}_i^{\nu}}) \), is computed as

\[
\begin{align*}
\mu_{\tilde{w}_i^{\nu}} &= \frac{1}{\lambda_{\tilde{w}_i^{\nu}}} \mu_{\tilde{w}_i^{\nu}} & (38) \\
\nu_{\tilde{w}_i^{\nu}} &= \frac{1}{\lambda_{\tilde{w}_i^{\nu}}} \nu_{\tilde{w}_i^{\nu}} & (39)
\end{align*}
\]

where \( \lambda_{\tilde{w}_i^{\nu}} = \max \nu_{\tilde{w}_i^{\nu}} \) and \( \lambda_{\tilde{w}_i^{\mu}} = \max \mu_{\tilde{w}_i^{\mu}} \).

Step 12: Obtain the global priority weights [Section J].

With the normalized IF weight \( \tilde{w}_i \) in Equation (38) and Equation (39) and the normalized steady-state matrix \( \tilde{C}' \), the global priority weights \( \tilde{w} = (\mu_{\tilde{w}}, \nu_{\tilde{w}}) \) are obtained as follows:

\[
\begin{align*}
[\mu_{\tilde{w}}] &= [\mu_{\tilde{w}}] + \frac{[\mu_{\tilde{c}^{\nu}}]}{[\mu_{\tilde{c}^{\nu}}]} \left[ [\mu_{\tilde{c}^{\nu}}] \right] & (40) \\
[\nu_{\tilde{w}}] &= [\nu_{\tilde{w}}] + \frac{[\mu_{\tilde{c}^{\mu}}]}{[\mu_{\tilde{c}^{\mu}}]} \left[ [\mu_{\tilde{c}^{\mu}}] \right] & (41)
\end{align*}
\]

Step 13: Integrate this set of information (i.e., strategies, global priority weights \( \tilde{w} \)) into the next SC entity. Step 14: Perform Step 1 to Step 13 for the succeeding SC entities.

A graphical summary of the integrated methodology proposed in this work is presented in Fig. 5. Here, as in the case of any public sector SC, the demanding entity is the government.

4. An application in a government-funded research project

4.1. Case study information

Increasing the number of institutions performing research and development activities in the Philippines is the response of the higher education institutions (HEIs) to the mandate of the Commission on Higher Education (CHED) in building up the country’s research capabilities [97]. CHED is the Philippine government arm tasked to handle all relevant concerns related to higher education. This agenda set by CHED intends to improve the quality of higher education by establishing policy directives and a grant and incentive structure that prioritizes academic excellence [98]. Furthermore, a need to provide capacity-building programs to significantly improve the performance of HEIs in responding to pressing needs, particularly associated with the fourth industrial revolution, is identified by CHED [99]. Hence, they offered the Institutional Development and Innovation Grants (IDIG) program that will financially support institutions capable of delivering capability-building initiatives.

Cebu Technological University (CTU) is one of the HEIs financially supported by the IDIG program under the project “Creation of an Interdisciplinary Graduate Program and Courses for Applied Mathematics and Operations Research: As Tools for Innovation Studies”. The project aims to
address the underlying problem of the current inadequacy of academic programs in the local region, specifically in applied mathematics and operations research (AM&OR). Meanwhile, the Center for Applied Mathematics and Operations Research (CAMOR), based at CTU, is established to act as the research hub in spearheading high-impact research for stakeholders and HEIs in addressing pressing problems that can be modelled with tools in AM&OR. CAMOR also serves as one of the implementing arms of the IDIG program, carrying out the objectives and coordinating with various stakeholders for achieving those objectives. Since CAMOR is established within a state university, it must adhere to the procurement process guidelines in government transactions. Particularly, material acquisition associated with the project (i.e., setting up a laboratory) needs alignment with the Bids and Awards Committee (BAC). To ensure better outcomes in any project, competence in the procurement process becomes imperative [100]. Moreover [101], adds that stakeholders’ trust boosts selecting a suitably competent supplier since it increases the likelihood of helping meet project objectives. In addition, (a) cost, (b) delivery time, (c) quality, (d) innovation, (e) reputation, (f) response to customers, and (g) location are some of the criteria that should be evaluated [102].

However, by the time HEIs reached mid-March in 2020, COVID-19 had ravaged normal business operations as it spread globally. A nationwide lockdown was imposed, and HEIs were forced to conduct operations primarily via work-from-home (WFH) arrangements. As a response, HEIs in the country have established new normal conditions aligned with the national government, especially related to social

Fig. 4. depicted as a partitioned matrix of IF causal relationships.

Fig. 5. Methodological framework.
4.2. The proposed procedure

The application of the proposed framework in the case study is discussed in the following. Note that the required dataset of the case study is supplied as Supplementary Material.

Step 1: Obtain the requirements of CHED and the response strategies of CAMOR, BAC, and the supplier. These elements (i.e., requirements, strategies), shown in Table 2, are ideally generated through a focus group discussion of the public sector SC entities. The requirements of CHED are explicitly reflected in the project memorandum. The Director identified the response strategies of CAMOR in consultation with the rest of the staff of the research center. These requirements also capture the current COVID-19 related guidelines. Upon identifying these strategies, the BAC determines its response strategies along with the procurement protocols imposed by the government. Finally, the identified supplier develops its own strategies in response to the strategies set by the BAC.

Step 2: Obtain the priorities of CHED requirements. According to CHED, the priority ranking of the requirements is as follows: A11 ≥ A14 ≥ A15 ≥ A13 ≥ A12 ≥ A16. Then, CHED elicits judgments on the relative importance of the requirements via the evaluation scale presented in Table 3. Using Equation (30) and Equation (31), two optimization models in Equation (42) and Equation (43) are constructed to generate the initial IF priority weights. Equation (42) yields μA11 = 0.7343, μA12 = 0.0175, μA13 = 0.0350, μA14 = 0.1049, μA15 = 0.1049, μA16 = 0.0035, with ξ = 0.0001. On the other hand, Equation (43) produces νA11 = 0.0290, νA12 = 0.2045, νA13 = 0.1534, νA14 = 0.0966, νA15 = 0.1074, νA16 = 0.4091, with ζ = 0.0000.

\[
\min_\xi \quad \text{subject to:} \\
\frac{\mu_{A11}}{\mu_{A15}} - 7 \leq \xi; \quad \frac{\mu_{A14}}{\mu_{A15}} - 1 \leq \xi; \quad \frac{\mu_{A13}}{\mu_{A12}} - 3 \leq \xi; \quad \frac{\mu_{A12}}{\mu_{A13}} - 2 \leq \xi; \quad \frac{\mu_{A11}}{\mu_{A13}} - 5 \leq \xi; \\
\frac{\mu_{A14}}{\mu_{A13}} - 7 * 1 \leq \xi; \quad \frac{\mu_{A13}}{\mu_{A12}} - 1 * 3 \leq \xi; \quad \frac{\mu_{A12}}{\mu_{A11}} - 3 * 2 \leq \xi; \quad \frac{\mu_{A11}}{\mu_{A12}} - 2 * 5 \leq \xi; \\
\mu_{A11} \geq \mu_{A14} \geq \mu_{A13} \geq \mu_{A12} \geq \mu_{A16}
\]  

(42)
The model elements of the case public sector SC.

Table 2
The model elements of the case public sector SC.

| Codes | Model elements |
|-------|----------------|
| CHED (grant funding institution) requirements | |
| A11 | All project objectives are achieved. |
| A12 | Project timelines are met. |
| A13 | Project objectives are implemented within the specified budget. |
| A14 | The framework of the graduate program is effectively developed. |
| A15 | Courses in applied mathematics and operations research are enhanced to respond to pressing needs. |
| A16 | Quality equipment is purchased. |
| CAMOR (implementing institution) strategies | |
| A21 | Maintaining public health and safety in project implementation |
| A22 | Creating an overarching plan of operations within timelines and budget |
| A23 | Synchronizing workforce with the overarching plan |
| A24 | Implementing “lean” operations |
| A25 | Carrying out coordination efforts with the needed stakeholders |
| A26 | Initiating effective communication channels among stakeholders |
| A27 | Setting quality product and service specifications |
| BAC (purchasing department) strategies | |
| A31 | Maintaining public health and safety in transactions |
| A32 | Complying with government procurement protocols |
| A33 | Implementing coordination activities with the requesting unit and the supplier |
| A34 | Implementing “lean” office |
| A35 | Maintaining a portfolio of quality suppliers of products and services |
| A36 | Establishing a list of supplier evaluation criteria |
| A37 | Procuring products and services within specifications |
| A38 | Creating progress reports of purchased products |
| Supplier strategies | |
| A41 | Maintaining public health and safety in operations |
| A42 | Implementing an agile business model |
| A43 | Implementing responsive customer relationship management |
| A44 | Implementing “lean” service concepts |
| A45 | Implementing strict quality control measures |
| A46 | Implementing a competitive pricing policy |
| A47 | Implementing effective communication strategies to ensure accurate transactions |
| A48 | Meeting deadlines set for procurement requirements |

Following Step 4 of Section 3, the AP values are computed using

\[
\sum_{j=1}^{6} \mu_{x_{ij}} = 1
\]

\[
\mu_{x_{ij}} > 0, \quad \forall i = 1, \ldots, 6
\]

\[
\min_\xi \nu
\]

subject to:

\[
\frac{d_{x_{i1}}}{d_{x_{i2}}} - 7 \leq \zeta; \quad \frac{d_{x_{i1}}}{d_{x_{i2}}} - 1 \leq \xi; \quad \frac{d_{x_{i1}}}{d_{x_{i2}}} - 3 \leq \zeta; \quad \frac{d_{x_{i1}}}{d_{x_{i2}}} - 2 \leq \zeta; \quad \frac{d_{x_{i1}}}{d_{x_{i2}}} - 5 \leq \zeta
\]

\[
\frac{d_{x_{i1}}}{d_{x_{i2}}} - 7 + 1 \leq \zeta; \quad \frac{d_{x_{i1}}}{d_{x_{i2}}} - 1 + 3 \leq \xi; \quad \frac{d_{x_{i1}}}{d_{x_{i2}}} - 3 + 2 \leq \zeta; \quad \frac{d_{x_{i1}}}{d_{x_{i2}}} - 2 + 5 \leq \zeta
\]

\[
\nu_{x_{i1}} \leq \nu_{x_{i2}} \leq \nu_{x_{i3}} \leq \nu_{x_{i4}} \leq \nu_{x_{i5}} \leq \nu_{x_{i6}}
\]

\[
\sum_{j=1}^{6} \nu_{x_{ij}} = 1
\]

\[
\nu_{x_{ij}} > 0, \quad \forall i = 1, \ldots, 6
\]

The IF priority weights of the CHED requirements are shown in Table 4.

Step 3: Implement the IF-Kano for each CHED requirement. As discussed in Step 4 of Section 3, CHED elicits the satisfaction level for each requirement. With the 1–9 satisfaction rating, Table 5 displays the initial evaluation.

Following Step 4 of Section 3, the AP values are computed using Table 2.

Step 4: Aggregate the \( \hat{w} \) and the AP for each requirement \( i \). Equation (33) provides the adjusted IF priority weights (\( \hat{w} \)). Also, to allow us to rank the priorities of the requirements expressed in IFs, the ideal positive degree \( I(\cdot) \) of Definition 4 is used. Table 7 shows the \( \hat{w} \), the \( I(\hat{w}) \) which maps \( \hat{w} \) to \( \hat{r} \), and the corresponding rank of a given CHED requirement. It shows that \( A11 \geq A14 \geq A15 \geq A13 \geq A12 \geq A16 \). While it maintains the initial ranking of CHED requirements during the IF-FUCOM, it effectively assigns the appropriate priority weights for each requirement.

Step 5: Perform Step 2 to Step 4 to calculate the adjusted IF priority weights of CAMOR strategies. For brevity, the \( \hat{w} \), AP, and \( \hat{w} \) are shown in Table 8.

Step 6: Build the IFDM of the CHED requirements and CAMOR strategies. The IF causal relationships among requirements were elicited by CHED. On the other hand, CAMOR provides the IF causal relationships among identified strategies. Using the IF scale in Table 9, modified from Ref. [103]; the IFDM is developed and is shown in Table 10.

To attain the normalized steady-state matrix \( \tilde{C}^* \), it is necessary to carry out the computations in Equation (34) up to Equation (37). The resulting \( \tilde{C}^* \) is presented in Table 11. The Supplementary Material provides the required computations of the IFDM.

Step 7: Obtain the global priority vector.

Following the normalization of \( \tilde{w} \) in Table 8 using Equation (38) and Equation (39) and the normalized steady-state matrix \( \tilde{C} \) in Table 11, Equation (40) and Equation (41) generate the global priority vector \( \tilde{w}^* \) (i.e., shown in Table 12). The \( \tilde{w}^* \) vector then becomes inputs in the computation of the global priority vector of the next SC entity strategies (i.e., BAC). The main interest of Table 12 is to generate the priority weights of CAMOR strategies and identify those priority strategies as inputs to response efforts necessary for CAMOR in its participation in the public sector SC. The results, as depicted in Fig. 7, shows the following:

### Table 3
The evaluation scale for the IF-FUCOM.

| Rate | Linguistic scale | Corresponding IFS |
|------|------------------|------------------|
| 1    | Equal importance | (1.0) 9          |
| 2    | Weak importance  | (2.0) 75         |
| 3    | Moderate importance | (3.0) 7          |
| 4    | Moderate plus importance | (4.0) 55       |
| 5    | Strong importance | (5.0) 5          |
| 6    | Strong plus importance | (6.0) 35       |
| 7    | Very strong or demonstrated importance | (7.0) 3      |
| 8    | Very, very strong importance | (8.0) 15      |
| 9    | Extreme importance | (9.0) 1          |

Equation (32). These adjustment factors are shown in Table 6. For brevity, the computations are not presented here. Nevertheless, for tractability, they are provided in the Supplementary Material.

### Table 4
The IF priority weights of CHED requirements.

| CHED requirements | IF priority weights (\( \hat{w} \)) |
|-------------------|---------------------------------|
| A11               | (0.7343,0.0290)                |
| A12               | (0.0175,0.2045)                |
| A13               | (0.0350,0.1534)                |
| A14               | (0.1049,0.0966)                |
| A15               | (0.1049,0.1074)                |
| A16               | (0.0035,0.4091)                |
For brevity, we skip the detailed discussion of the steps in generating the priority strategies of the remaining SC entities. We present Table 13 for priorities among CHED requirements and CAMOR strategies. This ranking incorporates salient information on uncertainty, complexity, and synthesis of priorities among CHED requirements and CAMOR strategies.

Step 8: Repeat Step 2 to Step 7 to identify the priority strategies of BAC and the supplier.

For brevity, we skip the detailed discussion of the steps in generating the priority strategies of the remaining SC entities. We present Table 13 for priorities among CHED requirements and CAMOR strategies. This ranking incorporates salient information on uncertainty, complexity, and synthesis of priorities among CHED requirements and CAMOR strategies.

It must be pointed out that IF-Kano analysis was not performed in the supplier strategies as the supplier becomes the last entity in the case public sector SC. The IFDM of CAMOR and BAC strategies are presented in Table 14, while Table 15 shows the IFDM of BAC and supplier strategies.

The information in Table 13 and the information in Tables 14 and 15 are integrated following Step 7 in obtaining the global priority vectors for BAC and supplier strategies. The priority strategies for BAC are highlighted in Table 16, while the supplier priority strategies are presented in Table 17. Furthermore, a graphical presentation of the global priority vectors for BAC and supplier strategies are shown in Fig. 8 and Fig. 9, respectively.

Table 16 shows the following priority ranking of BAC strategies: A32 ≥ A23 ≥ A21 ≥ A26 ≥ A25 ≥ A24 ≥ A27. On the other hand, the supplier strategies generate the following priority ranking in Table 17: A41 ≥ A43 ≥ A47 ≥ A46 ≥ A44 ≥ A45 ≥ A42 ≥ A48.

5. Discussion

This study aims to provide a systematic approach in positioning the strategies of each entity in the SC in the public sector within the premise of the COVID-19 pandemic integrating the Kano-QFD with FUCOM-based decision maps under an intuitionistic fuzzy environment. Three processes are identified in the SC in the case study: (1) project planning, (2) material request, and (3) procurement. These processes involve four stakeholders: the funding institution (i.e., CHED), research institution (i.e., CAMOR), BAC, and the supplier. Unlike previous models, the proposed approach considers the individual capacity of each entity to conduct its tasks by utilizing the information (i.e., strategies, priorities) of the previous entity. In addition, the level of satisfaction of each strategy (or requirements), along with the notion of uncertainty in eliciting decisions, is integrated into the allocation of priority weights for each strategy. Identifying priority strategies by holistically taking into consideration the complexity and uncertainty of the decision problem enables strong integration of interests along with the SC, which is pivotal for the public sector in resource allocation decisions, policy design, and strategy development. Collectively, the proposed approach provides a synthesis of complex and uncertain information across the public sector SC for the delivery of public goods.

In the case study, the strategy with the highest priority weight in the project planning process is creating an overarching plan of operations within timelines and budget (A22). This result is highly relevant considering that in carrying out a large and complex operation, a systematic plan acceptable for all stakeholders involved (i.e., funding institution and research center) must establish first to accomplish predetermined targets. Moreover, a fundamental feature to project implementation within limited resources (e.g., time, budget) is creating a roadmap of operations necessary to ensure that all project objectives are achieved. Accordingly, decision-makers in the research center must balance the project scope against the constraints of schedule, budget, staff resources, and quality objectives. Consequently, this involves the second-ranked strategy, synchronizing the workforce with the overarching plans (A23). This is then followed by maintaining public health and safety in project implementation (A24), initiating effective communication channels among stakeholders (A26), carrying out...
### Table 10
The IFDM for CHED requirements and CAMOR strategies.

|    | A11   | A12   | A13   | A14   | A15   | A16   | A21   | A22   | A23   | A24   | A25   | A26   | A27   |
|----|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| A1 | (0,1) | (0.75,0.2) | (0.75,0.2) | (1,0.1) | (0.75,0.2) | (0,1) | (0,1) | (0,1) | (0,1) | (0,1) | (0,1) | (0,1) | (0,1) |
| A2 | (0.5,0.45) | (0.5,0.45) | (0.5,0.45) | (0.5,0.45) | (0.5,0.45) | (0,1) | (0,1) | (0,1) | (0,1) | (0,1) | (0,1) | (0,1) | (0,1) |
| A3 | (0.5,0.45) | (0.5,0.45) | (0.5,0.45) | (0.5,0.45) | (0.5,0.45) | (0,1) | (0,1) | (0,1) | (0,1) | (0,1) | (0,1) | (0,1) | (0,1) |
| A4 | (0.5,0.45) | (0.5,0.45) | (0.5,0.45) | (0.5,0.45) | (0.5,0.45) | (0,1) | (0,1) | (0,1) | (0,1) | (0,1) | (0,1) | (0,1) | (0,1) |
| A5 | (0.5,0.45) | (0.5,0.45) | (0.5,0.45) | (0.5,0.45) | (0.5,0.45) | (0,1) | (0,1) | (0,1) | (0,1) | (0,1) | (0,1) | (0,1) | (0,1) |
| A6 | (0.5,0.45) | (0.5,0.45) | (0.5,0.45) | (0.5,0.45) | (0.5,0.45) | (0,1) | (0,1) | (0,1) | (0,1) | (0,1) | (0,1) | (0,1) | (0,1) |
| A7 | (0.5,0.45) | (0.5,0.45) | (0.5,0.45) | (0.5,0.45) | (0.5,0.45) | (0,1) | (0,1) | (0,1) | (0,1) | (0,1) | (0,1) | (0,1) | (0,1) |

### Table 11
The normalized steady-state matrix $\tilde{C}$ for CHED requirements and CAMOR strategies.

|    | A11   | A12   | A13   | A14   | A15   | A16   | A21   | A22   | A23   | A24   | A25   | A26   | A27   |
|----|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| A1 | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) |
| A2 | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) |
| A3 | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) |
| A4 | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) |
| A5 | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) |
| A6 | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) |
| A7 | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) | (0.00035) |
coordination efforts with the needed stakeholders (A25), implementing lean operations (A24), and setting quality product and service specifications (A27), respectively. It is evident that maintaining public health emerges with a higher priority, which implies that achieving target requirements set by the government (i.e., CHED) requires a deliberate and careful effort in ensuring that public health is maintained.

On the other hand, complying with government procurement protocols (A32) is the priority for the material request process. Since the BAC is tasked to execute the necessary procedures for government compliance, this strategy, as the priority, seems to be a straightforward implication. Furthermore, since the BAC links CAMOR and the supplier, face-to-face interaction is inevitable for their operations. Thus, maintaining public health and safety in transactions (A31) as the second-ranked priority is crucial. The rest of the strategies are arranged as follows: implementing coordination activities with the requesting unit and the supplier (A33), implementing lean office (A34), procuring products and services within specifications (A37), establishing a list of supplier evaluation criteria (A36), maintaining a portfolio of quality suppliers of products and services (A35), and creating progress reports of purchased products (A38).

Maintaining public health and safety (A41) for the procurement process is the strategy with the highest priority weight. Since most activities carried out by the suppliers include face-to-face interaction with the stakeholders (i.e., delivery), implementing extra precautions are necessary measures for the safety of all stakeholders involved under the new normal conditions. This is followed by implementing responsive customer relationship management (A43), which implies that having an effective communication channel with the customer from the requested material specifications until after-procurement services is critical for ensuring the reliability of outcomes and accuracy in every transaction. Studies conducted by Refs. [104,105] revealed that collaborations and consistent communications among supply chain stakeholders have a crucial role in obtaining sustainable future support from SC partners and enhancing SC performance and customer satisfaction. Thus, suppliers must ensure that their facilities and capabilities are excellent, and there is an emphasis on customer orientation and open communication as well as inter-agency communication. The remaining strategies are sequenced as follows: implementing effective communication strategies to ensure accurate transaction (A47), implementing a competitive pricing policy (A46), implementing lean service concepts (A44), implementing strict quality control policies (A45), implementing an agile business model (A42), and meeting deadlines set for procurement requirements (A48).

Table 12
The global priority vector of CAMOR strategies.

| Elements | Global priority vector ($\hat{w}$) | $I(\hat{w})$ | Rank |
|----------|-----------------------------------|-------------|------|
| A11      | (0.5981, 0.0106)                  |             |      |
| A12      | (0.0033, 0.0419)                  |             |      |
| A13      | (0.0045, 0.0332)                  |             |      |
| A14      | (0.0817, 0.0654)                  |             |      |
| A15      | (0.0817, 0.0669)                  |             |      |
| A16      | (0.0091, 0.1648)                  |             |      |
| A21      | (0.1290, 0.1033)                  | 0.5644      | 3    |
| A22      | (0.2272, 0.0095)                  | 0.6245      | 1    |
| A23      | (0.1575, 0.1188)                  | 0.5776      | 2    |
| A24      | (0.0919, 0.1491)                  | 0.5378      | 6    |
| A25      | (0.1249, 0.1501)                  | 0.5552      | 5    |
| A26      | (0.1053, 0.0402)                  | 0.5568      | 4    |
| A27      | (0.0765, 0.1257)                  | 0.5331      | 7    |

Fig. 7. Distribution of the global priority vector of CAMOR strategies.
The disruptions of the COVID-19 pandemic foster the need for integration among entities in the public sector SCs and establishing shared value for all stakeholders. The public sector SCs have been affected by degraded demand, facilities that were shut down, fiscal restrictions, and public health measures resulting in more complex processes. The integrated approach and the case strategies in this study provide a spectrum of benefits to decision-makers of the public sector SCs. Priority strategies in the upstream are tightly integrated downstream, forcing close coordination among members of the SC. These strategies accelerate efforts by creating an enabling environment, strengthening SCs, and encouraging product and service innovation in the public sector. In effect, it better augments the socio-economic conditions of the public as the receiver of goods and the human resources supporting the SC. The study insights contribute to the efficacy of public sector SCs in responding and adapting to disruptions fueled by the pandemic. The conceptual SC design and its demonstration via a case study emphasize the significance of cooperation among entities in translating government requirements into tangible goods that would uplift socio-economic conditions of the public while maintaining cost-efficiency, public welfare, enhanced customer service, and upholding public health standards.

In particular, the proposed framework captures a synthesis of strategies necessary for the public sector SC entities. In the case study, note that the priority requirement from a government entity (i.e., CHED) is meeting all project objectives. This requirement is well reflected in the priority strategies of CAMOR (i.e., the upstream entity) by highlighting the significance of creating an overarching plan of operations, synchronizing workforce, and maintaining public health and safety in project implementation strategies. The first two are almost straightforward; however, it is surprising that maintaining public health and safety becomes equally important in achieving priority CHED requirements. While still under the COVID-19 pandemic, disruptions caused by lockdowns, infections, and hospitalizations triggered by deliberately ignoring public health protocols may hamper operations on a certain scale, affecting the overall project timelines and incurring some overall costs. This agenda is well-represented in the downstream entity (i.e., BAC), which underlines the importance of complying with government procurement protocols and public health in achieving the priority strategies of the upstream SC entity (i.e., CAMOR). Compliance with procurement guidelines ensures prompt implementation of project activities, as failure to abide by these guidelines would force the government to stop the implementation for possible fraud. In addition, the downstream entity emphasizes maintaining public health to avoid delays due to viral spread. These agenda of the BAC are also reflected in the agenda of the downstream entity (i.e., the supplier). In the priority strategies of the supplier, maintaining public health and safety in
7. Conclusion and future work

In summary, this study introduces a framework for synthesizing strategies in otherwise isolated entities in public sector supply chains. The proposed framework intends to integrate the operations of entities in public sector SCs. The integration of information yields three primary benefits: (1) alignment of objectives of the entities, (2) synchronization of processes in otherwise independently operating entities, and (3) maximization of product and service quality. These benefits lead to the maximization of the satisfaction level of each public sector SC entity.

The framework introduced in this work is developed based on an intuitionistic fuzzy environment. This platform addresses uncertainty in decisions involved in public sector SCs. Accounting for such uncertainties allows the proposed framework to systematically process subjective judgments and hesitations of decision-makers, which are operations emerges on top of the priority list, followed by responsive customer relations and effective communication. These strategies adequately address the strategies of the upstream entity (i.e., BAC). Responsive customer relations coupled with effective communication would ensure compliance with government procurement protocols. In addition, maintaining public health safeguards against disruption in operations and meeting the requirements of the upstream entities. With the proposed method, each entity maintains and reflects the transition of information across the SC. Finally, although the case study demonstrated in this work contains idiosyncrasies, it is evident that a crucial mitigation effort in cushioning the impact of the pandemic is main
It is important to account for such uncertainties to obtain more robust estimations of parameters (i.e., priorities of strategies), which minimizes the risk of counterintuitive decisions that can be costly in public sector SCs. The use of IFS is also advantageous compared to stochastic approaches, which rely heavily on a manifold of data. Unlike private sector enterprises, data can be challenging to obtain in public sector SCs. Its use makes it possible to estimate the value of quality parameters (e.g., customer requirements) based on a few expert judgments. Conventional deterministic and stochastic approaches fail to account for the important factors highlighted above, which warrants the framework proposed in this work.

In addition, the integration of an analytic framework that systematically incorporates the crucial information on uncertainty, complexity, and priority into the Kano-QFD model effectively translates the priorities from upstream to downstream entities of the public sector SC. The integrative modelling framework is novel in this analysis, and some components are reported only in this work. Although rigorous comparisons of performance may be necessary, this work offers a starting point of discussion for future research in this work. For instance, the integration of IFS within the computational framework of the FUCOM has not been reported yet. Incorporating uncertainty through the IFS is a natural extension of eliciting judgments expressed in words. Likewise, the IFS extension of the FDMs is first demonstrated in this work. These components augment a robust model that effectively translates information from one entity to another entity in the SC.

In this work, the proposed framework is illustrated through a case study of a multi-level public sector SC in the Philippines. The case study highlights the applicability of the proposed framework not only in the case environment but also in other public sector SCs. For instance, the framework proposed here can be used in SCs involving the procurement of COVID-19 vaccines. In many countries, especially in the developing world, the chaos brought by the COVID-19 pandemic has made it difficult to synchronize processes, align objectives, and assure procurement and delivery of high-quality healthcare products and services to customers in the public sector SCs. The proposed framework can be employed in such environments as a decision support tool to address these problems.

However, certain limitations exist with the proposed framework. First, this study only uses a straightforward approach to the decision strategies of each SC entity. Given the complexity of public sector SCs, the multifaceted interaction among the strategies of each SC entity should be considered. Furthermore, the required computations of the proposed methodological framework may not be easily handled by stakeholders of the public sector SC. In this regard, analysts must design such a computational platform to facilitate the necessary computations. For instance, a manageable decision support system with a user-friendly interface may be developed for the proposed framework to enable decision-makers to effectively carry out the judgment elicitation after thoroughly identifying the relevant strategies in response to the conditions of the SC.

Future works may explore other fuzzy environments (e.g., Pythagorean fuzzy sets, rough sets, Fermatean fuzzy sets, Picture fuzzy sets, neutrosophic sets) in handling the uncertainty associated with the decision-making platform. The integration of the decision support framework proposed here into enterprise resource planning systems is an avenue for work in the domains of decision support systems. Lastly, case-specific studies may employ the proposed framework in planning the implementation of measures for post-pandemic socioeconomic development, which may require the synchronization of multi-level public sector SCs.
Author statement

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seps.2022.101340.

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Fig. 9. Distribution of the global priority vector of supplier strategies.
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