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Warehouse location selection with TOPSIS group decision-making under different expert priority allocations

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ABSTRACT
Warehouses are crucial infrastructures in supply chains. As a strategic task that would potentially impact various long-term agenda, warehouse location selection becomes an important decision-making process. Due to quantitative and qualitative multiple criteria in selecting alternative warehouse locations, the task becomes a multiple criteria decision-making problem. Current literature offers several approaches to addressing the domain problem. However, the number of factors or criteria considered in the previous works is limited and does not reflect real-life decision-making. In addition, such a problem requires a group decision, with decision-makers having different motivations and value systems. Analysing the varying importance of experts comprising the group would provide insights into how these variations influence the final decision regarding the location. Thus, in this work, we adopted the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to address a warehouse location decision problem under a significant number of decision criteria in a group decision-making environment. To elucidate the proposed approach, a case study in a product distribution firm was carried out. Findings show that decision-makers in this industry emphasise criteria that maintain the distribution networks more efficiently at minimum cost. Results also reveal that varying priorities of the decision-makers have little impact on the group decision, which implies that their degree of knowledge and expertise is comparable to a certain extent. With the efficiency and tractability of the required computations, the TOPSIS method, as demonstrated in this work, provides a useful, practical tool for decision-makers with limited technical computational expertise in addressing the warehouse location problem.

KEY WORDS
warehouse, location decision, multiple criteria decision-making, TOPSIS

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Introduction

Warehouses are infrastructures where raw materials or finished goods are stored before distribution for sale (Singh et al., 2018). They serve as storage facilities for enabling the movement of products through receiving, transferring, picking, and shipping. These processes contribute to the material flows in supply chains (Singh et al., 2018). Mostly, firms have warehouses within their physical vicinities where operations are under their control. When

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demand increases, firms (e.g., manufacturing) often require additional warehouse space; however, often, the option of building a warehouse may not be possible due to high investment costs (Wutthisirisart et al., 2015). In consequence, excess inventory that cannot be stored in warehouses controlled by the firms is transferred to third-party warehouses for which the firm pays rent, as well as incur labour and transportation costs for storing items and moving them back to the central warehouse (Demirel et al., 2010). These associated costs (i.e., warehousing costs) represent 24–29% of the total logistics cost (Singh et al., 2018). Due to their role in the effective management of the supply chain and its strategic importance, selecting a warehouse location becomes a crucial task.

A suitable warehouse location enhances the profitability of the firm and reduces the risk and uncertainty of the supply chain (Dey et al., 2016). It allows managers to respond quickly to demand flexibility (Jha et al., 2018). Consequently, it improves customer satisfaction, increasing the competitive advantage of the firm (Dey et al., 2016). Thus, locating a warehouse is a crucial process as it impacts capital investment, operating expenses, and customer service, and once in place, the decision becomes almost irreversible (Singh et al., 2018). Putting in the context of a supply chain network, a warehouse determines the efficiency and speed of supply chains (Singh et al., 2018). Vlachopoulou et al. (2001) argued that warehouse location selection was not only a question of choosing sites; instead, it involved comparing local characteristics of a market with the firm's overall corporate and marketing goals. Weber (1909, 1929) first introduced the warehouse location theory. The proposed problem locates a single warehouse to minimise the total travel distance between the warehouse and a set of locally distributed customers. Since then, the attention that warehouse location obtains in the current literature has increased dramatically.

Various methods were proposed to address a warehouse location problem, generally formulated as a mathematical program with solution techniques ranging from linear programming (Brunaud et al., 2018; Vanichchinchai & Apirakkhit, 2018; You et al., 2019) to search algorithms (Klose & Görtz, 2007; Huang & Li, 2008; An et al., 2014) and heuristics (Ghaderi & Jabalameli, 2013; Guastaroba & Speranza, 2014; Ho, 2015). Although single-objective optimisation methods are reported in the current literature, the consideration of multiple criteria is a direct consequence of the warehouse location problem due to the presence of various factors in the selection process. Among the early works on this domain, Lee et al. (1980) formulated an integer goal programming to a multi-criterion warehouse selection problem. However, formal mathematical programs limit the selection process only to consider criteria that can be articulated as a mathematical expression with defined measurement systems. This drawback pre-empts a holistic real-life decision-making problem due to the existence of subjective and objective criteria (Demirel et al., 2010; Dey et al., 2016). Thus, in addressing this limitation, multi-criterion decision-making (MCDM) methods have become a popular approach in the domain literature.

In the literature, works highlighting warehouse location selection went forward by presenting defined sets of criteria commonly used in the real-life decision-making process. These works used the criteria to identify the best warehouse location among a defined set of alternative sites. This process is contextualised around the realm of an MCDM where the best alternative is chosen among a specified set, subject to multiple and even conflicting criteria. More formally, the MCDM process can be defined as evaluating the alternatives for selection or ranking, using a number of qualitative and/or quantitative criteria that have different measurement units (Özcan et al., 2011). Among several MCDM methods, the use of the ELimination Et Choice Translating REality (ELECTRE) methods, the analytic hierarchy process (AHP), and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) can be highlighted as the primary methods of use (Özcan et al., 2011). The TOPSIS method was first proposed by Hwang and Yoon (1981) with the underlying principle that the best alternative is chosen based on maximising the distance from the negative ideal solution and minimising the distance from the positive ideal solution.

It is applicable in solving decisions with a large number of criteria, similar to the ELECTRE methods (Roy, 1990; Roy, 1991). This aspect overcomes one shortcoming of the AHP — its unsuitability of handling a large number of criteria or alternatives. Using the TOPSIS method, weights are determined through normalisation. This aspect overcomes the shortcomings of ELECTRE methods of possible biased data. These advantages of the TOPSIS compared to the AHP and ELECTRE make the TOPSIS more suitable for solving huge MCDM problems involving a huge number of criteria (e.g., warehouse location selection) (Özcan et al., 2011), especially where objective or quantitative data are given (Shih et al., 2007).

Hung and Cheng (2009) identified the main advantages of the TOPSIS: (1) simple, rational, comprehensible concept, (2) intuitive and clear logic that represents the rationale of human choice, (3) ease of computation and good computational efficiency, (4) a scalar value that accounts for both the best and worst alternatives' ability to measure the relative performance for each alternative in a simple mathematical form, and (5) possibility for visualisation. However, despite these advantages, using the TOPSIS method in solving a warehouse selection problem has limited insights. To the best of our knowledge, only Özcan et al. (2011), Roh et al. (2015), Büyüközkan and Uztürk (2017), and Roh et al. (2018) have explored such an approach. The TOPSIS method is applicable in solving MCDM problems with a large number of criteria, which was not explored in previous warehouse selection studies as a generic set of criteria was mostly used. Whereas in real-life decision-making, this domain problem requires a decision over a broad set of criteria. Additionally, a committee or a group of high-level managers of an organisation (or firm) along with external consultants or experts play an important role in the warehouse location selection problem (Dey et al., 2016). This expert group carefully chooses the right combination of selection criteria for the decision problem, along with important judgment elicitations necessary for the selection process. However, the obviously varied knowledge and expertise of these experts, have a significant impact on the overall group decision. Nevertheless, the current domain literature within the TOPSIS method fails to address this condition. Thus, the motivation of this study is to explore a warehouse selection problem involving a large number of criteria in a group decision-making environment, which is seen as a more realistic approach in warehouse location decision-making. The comprehensive criteria set is obtained by consolidating the significant criteria derived from the literature. In addition, of the varying importance of the analysis by experts comprising the group is put forward to provide insights into how these variations influence the final decision regarding the location. The contribution of this work is to carry out a group warehouse selection problem under a large number of criteria, which reflects real-life decision-making.

This paper is organised as follows. Section 2 presents some preliminary information on the approaches of warehouse location and the computational process of TOPSIS. Section 3 discusses the background of the case study and the proposed procedure. The insights of the findings are highlighted in Section 4. It ends with a conclusion and discussion of future work in Section 5.

1. Preliminaries

1.1. Approaches to warehouse location selection

Due to the finite number of location alternatives, usually pre-defined in the decision problem, to be evaluated under multiple, even conflicting criteria, the warehouse location selection could be appropriately framed as a multi-criterion decision-making (MCDM) problem (Özcan et al., 2011). As ill-defined formulations, MCDM problems often contain a criterion or criteria, from the set of criteria, which are subjective, with non-sharp information and limited measurement systems (Ocampo & Clark, 2015). The presence of both quantitative and qualitative factors (i.e., criteria) in the warehouse location selection process (Demirel et al., 2010) increases the complexity of the decision problem. As such, a decision regarding the location of a warehouse is generally one of the most critical and strategic decisions in logistics management and supply chain planning, mainly that such decision involves substantial capital investments and impacts future long-term capacity and inventory decisions (Demirel et al., 2010).

In a recent review by Yap et al. (2019) on the application of MCDM methods in site selection problems, to which warehouse location selection belongs, the analytic hierarchy process (AHP) of Saaty (1980) emerges as the widely used approach. In fact, one of the earliest works on solving warehouse location selection problem via MCDM methods was presented by Korpela and Tuominen (1996), with the AHP as their approach. Since then, the domain literature on this topic has flourished, and an increasing number of works that implemented MCDM methods and their hybrid, including their extensions via the use of fuzzy set theory, has been reported for the last decade. Some MCDM methods which were adopted in addressing the warehouse selection problem and closely related problems include approaches (i.e., pure or hybrid) based on the AHP (Alberto, 2000; García et al., 2014; Boltürk et al., 2016; Raut et al., 2017; Kabak & Keskin, 2018; Hakim & Kusumastuti, 2018; Singh et al., 2018; Franek & Kashi, 2017; Nevima & Kiszová, 2017), analytic network process — the generalisation of the AHP (Cheng et al., 2005), simple additive weighting (Chou et al., 2008; Dey et al., 2013), PROMETHEE II (Athawale et al., 2012), ELECTRE-II (He et al., 2017), the Choquet integral (Demirel et al., 2010), TOPSIS (Chu, 2002), VIKOR (Kutlu Gündoğdu & Kahraman, 2019), and cloud-based design optimisation (Temur, 2016), among others. Some works on this domain purposely combined two or more MCDM methods to overcome and complement the limitations of each technique and come up with a more powerful hybrid selection tool. In most cases, a different approach is adopted to address the prioritisation (or weighting) of the criteria and another tool for the ranking of alternative warehouse locations. These works include the integration of fuzzy TOPSIS-SAW-MOORA (Dey et al., 2016), fuzzy AHP-TOPSIS (Roh et al., 2018), and stochastic AHP and fuzzy VIKOR (Emeç & Akkaya, 2018). Note that this list is not intended to be comprehensive.

Aside from MCDM techniques, different methods have been explored in addressing warehouse selection decisions. In general, these techniques are associated with mathematical programming, with various solution techniques such as search algorithms and heuristics (Tyagi & Das, 1995; Rosenwein, 1996). An early work of Lee et al. (1980) first proposed an integer goal programming formulation for a multi-criterion warehouse location problem. Since then, various extensions have been developed, including mixed-integer linear programming (Kratica et al., 2014; Brunaud et al., 2018; Vanichchinchai & Apirakkhit, 2018; You et al., 2019), non-linear programming (Monthatipkul, 2016), multi-objective optimisation model (Xifeng et al., 2013), and second-order cone programming (Wagner et al., 2009), among others. Due to the complexity of the formulation, and entrapment to the local optima as a direct consequence, various techniques were developed, such as the Lagrangian relaxation approach (Ozsen et al., 2008; Nezhad et al., 2013), approximation algorithms (Huang & Li, 2008), local search algorithm (Cura, 2010), branch-and-price algorithm (Klose & Görtz, 2007), hybrid firefly-genetic algorithm (Rahmani & MirHassani, 2014), evolutionary multi-objective optimisation (Rakas et al., 2004), two-stage robust models and algorithms (An et al., 2014), and weighted Dantzig-Wolfe decomposition and the path-relinking combined method (Li et al., 2014). Search heuristics were also proposed, including hybrid multi-start heuristic (Resende & Werneck, 2006), a discrete variant of unconscious search (Ardjmand et al., 2014 and Kratica et al., 2014), math heuristic (Rath & Gutjahr, 2014), greedy heuristic and fix-and-optimise heuristic (Ghaderi & Jabalameli, 2013), kernel search heuristic (Guastaroba & Speranza, 2014), iterated tabu search heuristic (Ho, 2015), modified Clarke and Wright savings heuristic (Li et al., 2015), and swarm intelligence based on sample average approximation (Aydin & Murat, 2013). Interpretive structural modelling was also adopted to solve a warehouse selection problem that incorporates the sustainability agenda (Jha et al., 2018). When formal mathematical programs are used to address warehouse location decisions, the factors are expected to be quantitative and measurable in such a way that they can be expressed as formal mathematical equations or inequalities. However, in most real-life cases, some factors relevant in the decision domain (e.g., quality of life, social and cultural, security) are qualitative and subjective, which could not be expressed as mathematical statements. Thus, MCDM methods are considered a holistic approach in addressing both quantitative and qualitative factors in the selection of a warehouse location.

1.2. TOPSIS — the Technique of Order Preference Similarity to the Ideal Solution

In the context of MCDM applications for the selection of a warehouse location, the AHP, ELECTRE, and TOPSIS can be highlighted as the primary methods (Özcan et al., 2011). Özcan et al. (2011) made a comparative assessment of these methods, and the result is presented in Appendix 1. The assessment provides an insight into the performance of these methods in several areas. It is noteworthy that the TOPSIS has three main leverages: (1) the number outranking relations is one, which implies efficiency in judgment elicitations, (2) it is able to handle a large number of alternatives and criteria with objective and quantitative data, and (3) it generates a global, net order. These characteristics are appropriate in addressing a warehouse location selection, particularly when the number of criteria and alternatives is large, and the efficiency in generating the results from judgment elicitations is given a priority.

Initially proposed by Hwang and Yoon (1981), the foundation of TOPSIS lies at the notion of the distance function where the best alternative is chosen on the basis of maximising the distance from the negative ideal solution and minimising the distance from the positive ideal solution. Aside from location decision problems, TOPSIS has been used in a broad application domain, such as performance evaluation with the use of financial investment decisions (Kim et al., 1997), and financial ratios (Deng et al., 2000), personnel selection (Kelemenis & Askounis, 2010), strategy formulation (Ocampo, 2019), among others. Note that this list is not intended to be comprehensive. Reviews on the applications of TOPSIS have been reported by Behzadian et al. (2012), Shukla et al. (2017), and Yadav et al. (2018). TOPSIS leverages its advantages on simplicity and the tractability of the notion of distance based on ranking a set of alternatives (Chou et al. 2008; Özcanet al., 2011). It has efficient computational requirements due to its more straightforward evaluation techniques (Chou et al., 2008; Özcan et al., 2011; Roszkowska, 2011; Vavrek et al., 2017; Stankevičienė & Nikanorova, 2020).

The computational steps of the TOPSIS approach are provided below.

Step 1: Establish a decision matrix to evaluate the alternatives (e.g., supplier selection attributes) under different criteria. The structure of the evaluation can be expressed as follows:

$$D^k = \begin{pmatrix} f_{11}^k & f_{12}^k & \cdots & f_{1n}^k \\ f_{21}^k & f_{22}^k & \cdots & f_{2n}^k \\ \vdots & \vdots & \ddots & \vdots \\ f_{m1}^k & f_{m2}^k & \cdots & f_{mn}^k \end{pmatrix} \quad (1)$$

where f_{ij}^k, $i = 1, \dots, m$, $j = 1, \dots, n$, $k = 1, \dots, M$, represents the evaluation score on the performance (or relevance) of the ith alternative on the jth criterion, elicited by the kth decision-maker.

Step 2: Aggregate the individual decision matrices using an aggregation function. One of the highly adopted aggregation functions is the arithmetic mean. Thus, the aggregate score f_{ij} can be obtained as $f_{ij} = \sum_{k=1}^{M} f_{ij}^k$. The resulting aggregate decision matrix is shown in Equation (2).

$$D = \begin{pmatrix} f_{11} & f_{12} & \cdots & f_{1n} \\ f_{21} & f_{22} & \cdots & f_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ f_{m1} & f_{m2} & \cdots & f_{mn} \end{pmatrix} \quad (2)$$

Step 3: Obtain the priority weights of the criteria. The priority weight of a criterion j is expressed as w_j. Any prioritisation technique generates this. Note that the TOPSIS approach provides no specific method for obtaining the priority weights of the criteria.

Step 4: Calculate the normalised decision matrix $R = (r_{ij})_{m \times n}$. The normalised value r_{ij} is obtained as:

$$r_{ij} = \frac{f_{ij}}{\left(\sum_{i=1}^{m} f_{ij}^2\right)^{\frac{1}{2}}} \quad \forall i = 1, \dots, m, j = 1, \dots, n \quad (3)$$

Step 5: Calculate the weighted normalised decision matrix $V = (v_{ij})_{m \times n}$. Each element denoted as v_{ij}, is obtained by

$$v_{ij} = r_{ij} \times w_j \quad \forall i = 1, \dots, m, j = 1, \dots, n \quad (4)$$

Step 6: Determine the positive ideal solution (PIS), denoted by V^+, and the negative ideal solution (NIS), denoted by V^-:

$$V^+ = \{v_1^+, \dots, v_n^+\} = \left\{\left(\max_i v_{ij} : j \in J_1\right), \left(\min_i v_{ij} : j \in J_2\right)\right\} \quad (5)$$

$$V^- = \{v_1^-, \dots, v_n^-\} = \left\{\left(\min_i v_{ij} : j \in J_1\right), \left(\max_i v_{ij} : j \in J_2\right)\right\} \quad (6)$$

where J_1 is associated with the benefit (i.e., maximising) criteria, and J_2 is associated with the cost (i.e., minimising) criteria.

Step 7: Calculate the separation measures, using the m-dimensional Euclidean distance. The separation measure D_i^+ of each alternative i from the PIS is given as

$$D_i^+ = \left\{\sum_{j=1}^{n} \left(v_{ij} - v_j^+\right)^2\right\}^{\frac{1}{2}} \quad \forall i = 1, \dots, m \quad (7)$$

Similarly, the separation measures D_i^- of each alternative from the NIS is as follows:

$$D_i^- = \left\{\sum_{j=1}^{n} \left(v_{ij} - v_j^-\right)^2\right\}^{\frac{1}{2}} \quad \forall i = 1, \dots, m \quad (8)$$

Step 8: Calculate the relative closeness to the ideal solution and rank the alternatives in descending order. The relative closeness coefficient of the alternative j with respect to PIS V^+ can be expressed as:

$$C_i = \frac{D_i^-}{D_i^- + D_i^+} \quad \forall i = 1, \dots, m \quad (9)$$

2. Proposed procedure: TOPSIS group decision-making for the problem of warehouse location selection

2.1. Case-study background

ABC-G Enterprises is a product distributor of one of the largest brewing companies in the Philippines. It is a local distributor which is located in Cebu, an island in the central Philippines. With an increasing trend for the demand for their products, the company is in the process of finding a new location where they can build their second warehouse. The new warehouse is intended to stock a significant volume of their products to respond to an expected increase in customer demand. Two possible location alternatives were identified by ABC-G Enterprises. One possible location is at a 10-kilometre distance from their current headquarters, with an area of around 380 square meters. The second alternative has an area of approx. 300 square meters and is located within a 9-kilometre distance. Aside from the available area and the distance of the possible location, the company is also considering other salient criteria. For brevity, we refer to Talamban warehouse and Compostela warehouse for the first and second alternative, respectively. In determining the best location, the final decision lies with the administration team, which is composed of the President, Administration Manager, Senior Manager, and Assistant Manager, who are usually involved in making the crucial decisions of the company. Thus, there is a need for ABC-G Enterprises to carry out an analytic multi-criterion group decision-making process to identify the best location for the warehouse.

2.2. Computational steps

The proposed TOPSIS group decision-making process in this work consists of the following steps:

Step 1: Set up the decision warehouse location selection problem.

The decision problem is shown in Fig. 1. It shows the evaluation of two alternative warehouses (i.e., Talamban Warehouse and Compostela Warehouse) under 22 selection criteria. Current literature offers a number of selection criteria for warehouse location selection. Appendix 2 presents the majority of these criteria. These criteria are generic to some extent but may not be applicable in some cases, depending on the decision problem under consideration. The two warehouse location alternatives are evaluated with this set of criteria. Table 1 presents these criteria, corresponding codes for the brevity of presentation, and a brief description.

Step 2: Assign the importance weights of the expert decision-makers.

For this work, the administration team, which is composed of four members, becomes the expert group tasked to elicit judgments within the TOPSIS approach. Thus, the proposed approach becomes a TOPSIS group decision-making problem. However, in this case, the members of the expert group are non-

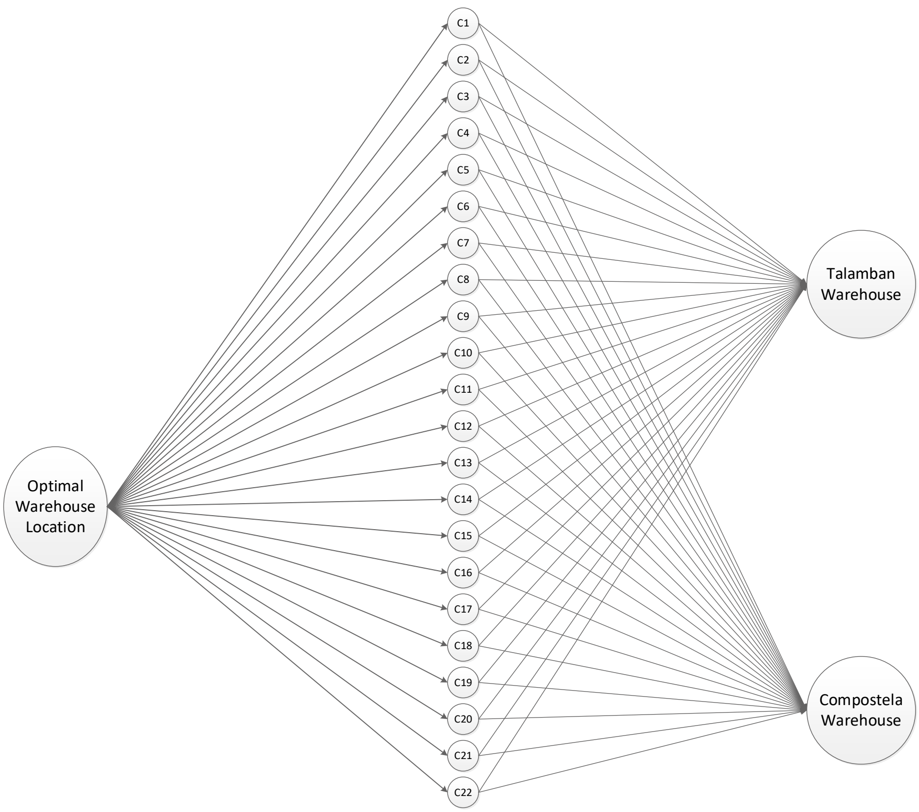

Fig. 1. Case for the problem of the warehouse location selection

Tab. 1. The set of criteria for the case of warehouse location selection

Code	Criteria	Description
C1	Unit price	Refers to the unit price per square metre of land
C2	Transportation cost	Relates to costs associated with the transportation facilities, and alternative transportation types
C3	Logistics cost	Relates to the costs of transferring products from the warehouse to their destinations
C4	Proximity to the leading supplier	The distance from the warehouse to the main supplier
C5	Proximity to customers	The distance from the warehouse to the customers
C6	Availability of customers	Number of customers in the area of the warehouse
C7	Space availability	Adequate space should be available for the warehouse
C8	Accessibility to the road	Road infrastructure considering the trucking service and road conditions
C9	Accessibility to the seaport	Considers accessibility to the seaport and distance from the warehouse
C10	Accessibility to the airport	Considers accessibility to the airport and distance from the warehouse
C11	Existence of modes of transportation	Availability of different transportation types in the location
C12	Quality and reliability of modes of transportation	Transportation service between the customer, supplier, and the warehouse
C13	Telecommunication systems	Communication facilities and technologies of the warehouse
C14	Zoning and construction plan	Different development plans, implementations, and arrangements of local administrations at alternative locations
C15	Industrial regulations laws	Various laws and arrangements at the alternative locations
C16	Security of region	Refers to the rate of loss by robbery, presence of organised crime, security personnel, and security systems
C17	Traffic access	Refers to the capacity of handling a large volume of traffic and providing ease of access to transportation infrastructure and traffic-related services
C18	Political stability	Relates to political change or stable political decisions
C19	Social stability	Risk of protests against the government
C20	Economic stability	A significant level of output growth and low and stable inflation
C21	Impact on ecological landscape	Maintains or improves the original landscape without damaging the city's image
C22	Condition of public facilities	Requires public goods, such as roads, communication, power supply, and water to function properly

Tab. 2. Rating scale for each criterion

Scale	Equivalent rating score
Very important	10
Fairly important	9
Important	7
Slightly important	5
Least important	3
Not important at all	1
Intermediate values between the two adjacent judgments	2, 4, 6, 8

Tab. 3. Importance weights of decision-makers based on S1, S2, S3

Decision-makers	Priority weights of decision-makers based on		
	S1	S2	S3
President	0.2258	0.2903	0.2500
Administration Manager	0.2258	0.2581	0.2500
Senior Manager	0.2581	0.2258	0.2500
Assistant Manager	0.2903	0.2258	0.2500

homogeneous in their expertise of the decision problem, as well as their power in decision-making within the company. Thus, the aggregation described in Step 2 must be revised. Instead, expert decision-makers are assigned corresponding priority weights. These weights represent the importance of their inputs to the group decision. One crucial point that must be addressed in the process of generating these weights. To address this, three possible scenarios were explored; that is, three sets of priority weights of decision-makers were generated. Priority weights were obtained based on (S1) the level of their expertise in warehouse location selection, (S2) their power in making decisions, (S3) equal weights. Table 2 provides the rating scale that was used to generate the importance weights of the decision-makers. The weights of the decision-makers based on the three scenarios (i.e., S1, S2, S3) are shown in Table 3.

Based on S1, the Assistant Manager got the highest priority since it has a better knowledge of the warehouse operations. The S2 scenario yields the President's judgments with the highest weight as it has the most significant power in making decisions for the company. Finally, Table 3 shows with equal priority weights, that the level of influence of the four decision-makers on the warehouse location selection is equal.

Step 3: Generate the priority weights of the criteria. Decision-makers were asked to rate the importance of each criterion on a scale from 1 to 10, where 1 and 10 representing the lowest and highest importance, respectively. With S1, S2, and S3, three sets of priority weights were also generated for the criteria set. Table 4 presents the criteria weights on the three different scenarios.

Tab. 4. Criteria weights for S1, S2, and S3

Criteria	President	Admin Manager	Senior Manager	Assistant Manager	Weights for S1	Weights for S2	Weights for S3
C1	10	10	10	10	0.0758	0.0759	0.0759
C2	9	8	9	9	0.0665	0.0663	0.0664
C3	6	5	7	6	0.0457	0.0453	0.0455
C4	9	9	10	10	0.0724	0.0717	0.0721
C5	8	8	9	10	0.0670	0.0659	0.0664
C6	7	6	7	7	0.0514	0.0512	0.0512
C7	8	8	7	9	0.0609	0.0607	0.0607
C8	8	9	7	9	0.0626	0.0627	0.0626
C9	3	1	2	1	0.0130	0.0137	0.0133
C10	1	2	1	1	0.0093	0.0095	0.0095
C11	5	5	4	5	0.0360	0.0362	0.0361
C12	7	8	8	9	0.0612	0.0602	0.0607
C13	7	6	6	5	0.0450	0.0460	0.0455
C14	4	3	4	2	0.0242	0.0250	0.0247
C15	6	7	6	7	0.0494	0.0492	0.0493
C16	8	7	7	8	0.0570	0.0570	0.0569
C17	8	8	9	9	0.0648	0.0641	0.0645
C18	5	5	4	3	0.0316	0.0328	0.0323
C19	4	2	3	2	0.0205	0.0213	0.0209
C20	4	3	3	3	0.0245	0.0250	0.0247
C21	1	1	2	1	0.0095	0.0093	0.0095
C22	6	7	6	8	0.0516	0.0509	0.0512

Table 4 shows the weights of each criterion for all scenarios, i.e., S1, S2, and S3. It must be noted that the weights of the criteria presented in Table 4 are aggregate weights concerning the corresponding importance of the decision-makers in each scenario, as shown in Table 3. For instance, the weight of C1 for S1, written as w_1^{S1}, is computed using the following:

$$w_1^{S1} = \frac{\sum_k x_{1k}^{S1} \omega_k^{S1}}{\sum_j \sum_k x_{jk}^{S1} \omega_k^{S1}} \quad (10)$$

where w_1^{S1} denotes the weight of criterion 1 in S1, x_{1k}^{S1} is the score of criterion 1 under S1 as elicited by decision-maker k, and ω_k^{S1} represents the weight of decision-maker k under S1. For instance,

$$w_1^{S1} = \frac{(10\times0.2258)+(10\times0.2258)+(10\times0.2581)+(10\times0.2903)}{131.8710} = 0.0758$$

Step 4: Decision-makers elicit judgments on the decision matrix. Using the rating scale for cost criteria (i.e., Table 5), and benefit criteria (i.e., Table 6), decision-makers elicit judgments on the performance of the jth alternative (i.e., warehouse) on the ith criterion.

The decision matrix is shown in Table 7.

Step 5: Generate aggregate decision matrices. Three aggregate decision matrices were generated, which corresponded to S1, S2, and S3 scenarios. Since the decision-makers had different importance weights at different scenarios, the aggregation function described in Step 2 of Section 2.2 had to be revised. To incorporate the importance weights of the decision-makers, the aggregation function is developed in Equation (11).

$$f_{ij}^{\sigma} = \frac{1}{4} \sum_k f_{ij}^{k,\sigma} \omega_k^{\sigma} \quad (11)$$

where f_{ij}^{σ} represents the aggregate performance score of the ith alternative (i.e., warehouse) with respect to jth criterion, under scenario σ (i.e., S1, S2, S3), $f_{ij}^{k,\sigma}$ is the score of the ith alternative with respect to jth criterion, under scenario σ evaluated by the kth decision-maker, and ω_k^{σ} is the importance weight of decision-maker k under scenario σ. The aggregate decision matrices are shown in Table 8.

For instance, using Equation (11), the value of f_{11}^{S1} can be obtained:

$$f_{11}^{S1} = \frac{(4 \times 0.2258) + (5 \times 0.2258) + (5 \times 0.2580) + (4 \times 0.2932)}{4} = 1.1210$$

Step 6: Calculate the normalised decision matrices. Using Equation (3), the normalised decision matrices are obtained.

Step 7: Calculate the weighted normalised decision matrices. Using Equation (4) with inputs from the priority weights of the criteria under the different scenarios, the weighted normalised decision matrices are obtained. Table 10 presents these matrices.

Step 8: Determine V^+ and V^- for S1, S2, and S3.

The PIS (V^+) and the NIS (V^-) are obtained using Equation (5) and Equation (6), respectively. Table 11 describes these values.

Step 9: Generate the separation measures D_i^+ and D_i^-. The separation measures D_i^+ and D_i^- are obtained using Equation (7) and Equation (8), respectively. The results are shown in Table 12.

Tab. 5. Rating scale for the cost criteria

Scale	Rating
Very Poor (VP)	10
Poor (P)	9
Medium Poor (MP)	7
Fair (F)	5
Good (G)	3
Very Good (VG)	1
Intermediate values between the two adjacent judgments	8, 6, 4, 2

Tab. 6. Rating scale for the benefit criteria

Scale	Rating
Poor (P)	1
Medium Poor (MP)	3
Fair (F)	5
Medium Good (MG)	7
Good (G)	9
Very Good (VG)	10
Intermediate values between the two adjacent judgments	2, 4, 6, 8

Tab. 7. Decision matrix

Criteria	President		Administration Manager		Senior Manager		Assistant Manager	
	Talamban	Compostela	Talamban	Compostela	Talamban	Compostela	Talamban	Compostela
C1	4	3	5	4	5	3	4	3
C2	3	4	4	5	3	5	3	4
C3	3	4	4	5	3	5	3	4
C4	9	1	1	9	9	1	8	1
C5	9	7	9	6	9	7	10	6
C6	9	7	9	6	9	7	10	6
C7	9	10	8	9	8	10	7	8
C8	9	10	9	10	10	8	9	10
C9	1	1	1	1	1	1	1	1
C10	1	1	1	1	1	1	1	1
C11	9	9	9	9	9	9	10	10
C12	9	9	9	9	9	9	10	10
C13	10	10	9	9	9	9	10	10
C14	5	9	4	9	5	9	4	9
C15	5	9	4	9	9	5	4	9
C16	8	9	8	9	8	7	4	9
C17	4	7	4	7	5	7	4	8
C18	8	8	8	8	8	8	9	9
C19	9	9	8	9	7	9	9	9
C20	10	7	1	6	10	7	9	6
C21	10	10	10	10	10	10	9	9
C22	10	10	9	9	9	9	10	10

Tab. 8. Aggregate decision matrices

Criteria	S1		S2		S3	
	Talamban	Compostela	Talamban	Compostela	Talamban	Compostela
C1	1.1210	0.8065	1.1210	0.8145	1.1250	0.8125
C2	0.8065	1.1210	0.8145	1.1210	0.8125	1.1250
C3	0.8065	1.1210	0.8145	1.1210	0.8125	1.1250
C4	1.7258	0.7016	1.6774	0.7661	1.6875	0.7500
C5	2.3226	1.6210	2.3065	1.6290	2.3125	1.6250
C6	2.3226	1.6210	2.3065	1.6290	2.3125	1.6250
C7	1.9839	2.2984	2.0161	2.3226	2.0000	2.3125
C8	2.3145	2.3710	2.3065	2.3871	2.3125	2.3750
C9	0.2500	0.2500	0.2500	0.2500	0.2500	0.2500
C10	0.2500	0.2500	0.2500	0.2500	0.2500	0.2500
C11	2.3226	2.3226	2.3065	2.3065	2.3125	2.3125
C12	2.3226	2.3226	2.3065	2.3065	2.3125	2.3125
C13	2.3790	2.3790	2.3790	2.3790	2.3750	2.3750
C14	1.1210	2.2500	1.1290	2.2500	1.1250	2.2500
C15	1.3790	1.9919	1.3548	2.0242	1.3750	2.0000
C16	1.7097	2.1210	1.7742	2.1371	1.7500	2.1250
C17	1.0645	1.8226	1.0565	1.8065	1.0625	1.8125
C18	2.0726	2.0726	2.0565	2.0565	2.0625	2.0625
C19	2.0645	2.2500	2.0726	2.2500	2.0625	2.2500
C20	1.9194	1.6210	1.8629	1.6290	1.8750	1.6250
C21	2.4274	2.4274	2.4435	2.4435	2.4375	2.4375
C22	2.3790	2.3790	2.3790	2.3790	2.3750	2.3750

Tab. 9. Normalised decision matrices

CRITERIA	S1		S2		S3	
	TALAMBAN	COMPOSTELA	TALAMBAN	COMPOSTELA	TALAMBAN	COMPOSTELA
C1	0.8118	0.5840	0.8090	0.5878	0.8107	0.5855
C2	0.5840	0.8118	0.5878	0.8090	0.5855	0.8107
C3	0.5840	0.8118	0.5878	0.8090	0.5855	0.8107
C4	0.9264	0.3766	0.9096	0.4154	0.9138	0.4061
C5	0.8200	0.5723	0.8168	0.5769	0.8182	0.5749
C6	0.8200	0.5723	0.8168	0.5769	0.8182	0.5749
C7	0.6534	0.7570	0.6555	0.7552	0.6542	0.7564
C8	0.6985	0.7156	0.6949	0.7192	0.6976	0.7165
C9	0.7071	0.7071	0.7071	0.7071	0.7071	0.7071
C10	0.7071	0.7071	0.7071	0.7071	0.7071	0.7071
C11	0.7071	0.7071	0.7071	0.7071	0.7071	0.7071
C12	0.7071	0.7071	0.7071	0.7071	0.7071	0.7071
C13	0.7071	0.7071	0.7071	0.7071	0.7071	0.7071
C14	0.4459	0.8951	0.4485	0.8938	0.4472	0.8944
C15	0.5692	0.8222	0.5562	0.8310	0.5665	0.8240
C16	0.6276	0.7786	0.6388	0.7694	0.6357	0.7719
C17	0.5043	0.8635	0.5048	0.8632	0.5057	0.8627
C18	0.7071	0.7071	0.7071	0.7071	0.7071	0.7071
C19	0.6761	0.7368	0.6775	0.7355	0.6757	0.7372
C20	0.7640	0.6452	0.7528	0.6583	0.7557	0.6549
C21	0.7071	0.7071	0.7071	0.7071	0.7071	0.7071
C22	0.7071	0.7071	0.7071	0.7071	0.7071	0.7071

Tab. 10. Weighted normalised decision matrices

CRITERIA	S1		S2		S3	
	TALAMBAN	COMPOSTELA	TALAMBAN	COMPOSTELA	TALAMBAN	COMPOSTELA
C1	0.0616	0.0443	0.0614	0.0446	0.0615	0.0444
C2	0.0389	0.0540	0.0390	0.0537	0.0389	0.0538
C3	0.0267	0.0371	0.0266	0.0366	0.0267	0.0369
C4	0.0671	0.0273	0.0652	0.0298	0.0659	0.0293
C5	0.0550	0.0384	0.0538	0.0380	0.0543	0.0382
C6	0.0421	0.0294	0.0418	0.0295	0.0419	0.0295
C7	0.0398	0.0461	0.0398	0.0458	0.0397	0.0459
C8	0.0437	0.0448	0.0435	0.0451	0.0437	0.0449
C9	0.0092	0.0092	0.0097	0.0097	0.0094	0.0094
C10	0.0066	0.0066	0.0068	0.0068	0.0067	0.0067
C11	0.0254	0.0254	0.0256	0.0256	0.0255	0.0255
C12	0.0432	0.0432	0.0426	0.0426	0.0429	0.0429
C13	0.0318	0.0318	0.0325	0.0325	0.0322	0.0322
C14	0.0108	0.0217	0.0112	0.0223	0.0110	0.0221
C15	0.0281	0.0406	0.0274	0.0409	0.0280	0.0407
C16	0.0358	0.0444	0.0364	0.0439	0.0362	0.0439
C17	0.0327	0.0560	0.0324	0.0554	0.0326	0.0557
C18	0.0223	0.0223	0.0232	0.0232	0.0228	0.0228
C19	0.0139	0.0151	0.0144	0.0157	0.0141	0.0154
C20	0.0187	0.0158	0.0188	0.0164	0.0186	0.0162
C21	0.0067	0.0067	0.0066	0.0066	0.0067	0.0067
C22	0.0365	0.0365	0.0360	0.0360	0.0362	0.0362

Tab. 11. V^+ and V^- for S1, S2, and S3

Criteria	S1		S2		S3	
C1	0.0443	0.0616	0.0446	0.0614	0.0444	0.0615
C2	0.0389	0.0540	0.0390	0.0537	0.0389	0.0538
C3	0.0267	0.0371	0.0266	0.0366	0.0267	0.0369
C4	0.0671	0.0273	0.0652	0.0298	0.0659	0.0293
C5	0.0550	0.0384	0.0538	0.0380	0.0543	0.0382
C6	0.0421	0.0294	0.0418	0.0295	0.0419	0.0295
C7	0.0461	0.0398	0.0458	0.0398	0.0459	0.0397
C8	0.0448	0.0437	0.0451	0.0435	0.0449	0.0437
C9	0.0092	0.0092	0.0097	0.0097	0.0094	0.0094
C10	0.0066	0.0066	0.0068	0.0068	0.0067	0.0067
C11	0.0254	0.0254	0.0256	0.0256	0.0255	0.0255
C12	0.0432	0.0432	0.0426	0.0426	0.0429	0.0429
C13	0.0318	0.0318	0.0325	0.0325	0.0322	0.0322
C14	0.0217	0.0108	0.0223	0.0112	0.0221	0.0110
C15	0.0406	0.0281	0.0409	0.0274	0.0407	0.0280
C16	0.0444	0.0358	0.0439	0.0364	0.0439	0.0362
C17	0.0560	0.0327	0.0554	0.0324	0.0557	0.0326
C18	0.0223	0.0223	0.0232	0.0232	0.0228	0.0228
C19	0.0151	0.0139	0.0157	0.0144	0.0154	0.0141
C20	0.0187	0.0158	0.0188	0.0164	0.0186	0.0162
C21	0.0067	0.0067	0.0066	0.0066	0.0067	0.0067
C22	0.0365	0.0365	0.0360	0.0360	0.0362	0.0362

Tab. 12. The separation measures and the relative closeness coefficients

	S1		S2		S3	
	Talamban	Compostela	Talamban	Compostela	Talamban	Compostela
	0.0351	0.0486	0.0348	0.0444	0.0347	0.0457
	0.0486	0.0351	0.0444	0.0348	0.0457	0.0347
	0.5808	0.4192	0.5607	0.4393	0.5681	0.4319
Rank	1	2	1	2	1	2

3. Results and discussion

In this work, three scenarios on the distribution of importance of the decision-makers' judgments were explored. Results show that these distributions yielded slight changes in the priorities of the warehouse location decision criteria. As shown in Table 4, the priorities yielded the following list:

C1(unit price)≻C4(proximity to the leading supplier)≻C2(transportation cost)≻C5(proximity to customers)≻C17(traffic access)≻C8(accessibility to the road)≻C7(space availability)≻C12(quality and reliability of modes of transportation)≻C16(security of region)≻C6(availability of customers)≻ C22(public facilities condition)

These criteria are identified by obtaining the median of all priorities and choosing those criteria which are above the median. Although small variations exist in the priority values and their corresponding ranks, the order of these criteria is reasonably stable under the three scenarios. This implies that the conditions of engaging more importance to expertise, decision-making power, or none at all have a limited impact on the group decision. A plausible way of explaining such a finding is that the members of the expert group (i.e., the administration team) have a comparable degree of knowledge and expertise on the operations of the warehouse as a distribution centre. With a closely related level of understanding of these operations, the priorities of these criteria would not significantly differ compared to a condition where experts have a more heterogeneous understanding of the domain problem. The ranking of priorities of the criteria indicates that the most crucial (i.e., top five) factors in warehouse location decision-making in the context of a product distribution firm include unit price, proximity to the leading supplier, transportation cost, proximity to customers, and traffic access. These criteria are highly associated with the economic considerations and efficient operations towards downstream and upstream supply chain members. It shows that decision-makers in this industry put more emphasis on maintaining the distribution networks more efficiently at minimum cost. This is consistent with the insights in the current literature. In the Philippines, as in many developing economies, traffic congestion is prevalent (i.e., most notably in the case location), and aiming to minimise the distances and maximise access to suppliers and customers is crucial in enhancing the productivity of the distribution operations. The unit price is associated with capital investment, which is a straightforward consideration in investment decisions. On the other hand, transportation cost is an operational cost, and keeping such a cost plays a huge role in maximising productivity.

With the use of group TOPSIS, the case study revealed that the Talamban site was the best warehouse location under the three different scenarios. This is also consistent with the observation which was obtained in the priorities of the criteria in relation to the distribution of priorities of decision-makers. It supports the previous claim that the expert knowledge and expertise regarding the decision of a warehouse location and the case problem are homogeneous to a considerable extent. It implies that the case firm must establish its warehouse at the identified location. It should be noted that the group decision using TOPSIS is robust on the distribution of expert priorities, as long as their knowledge and expertise are comparable.

Conclusions

The selection of a location for a warehouse requires considering multiple criteria used to evaluate the alternative sites, which is a straightforward implication of real-life decision-making. This set of criteria, often with numerous, contains both objective and subjective factors with non-sharp definitions and limited measurement scales. Furthermore, the presence of multiple decision-makers with different motivations and value systems is prevalent in such a strategic decision-making process. Understanding the impact of these differences in priorities is crucial in a group decision-making environment. In this article, with the use of TOPSIS, a warehouse location decision problem was considered with a significant number of criteria under a group decision-making structure with varying priorities of experts. A case study of a distribution firm was presented to illustrate the approach.

Under three different distribution scenarios of expert priorities (i.e., expertise, decision-making power, and equal weights), results showed that the unit price, proximity to the leading supplier, transportation cost, proximity to customers, and traffic access were considered the most important criteria for selecting a possible site for a warehouse. These findings imply two important insights. First, costs (i.e., investment capital and operational expenses) are important economic considerations in establishing a warehouse and maintaining it, which are inputs to warehouse location decisions. These costs are crucial factors in maintaining the overall profitability. Second, decision-makers put an emphasis on the efficient distribution operations to both downstream and upstream members of the supply chain. These factors, in general, are associated with maximising the productivity of the warehouse operations. Findings also reveal that the varying priorities of the decision-makers have little impact on the group decision, both at identifying priority criteria and the best warehouse location under TOPSIS, which implies that their degree of knowledge and expertise is comparable to a certain extent. This work demonstrates the efficacy of using the TOPSIS in warehouse location decisions under a significant number of criteria, along with an expert group who is tasked with making judgment elicitations. Due to the efficiency and tractability of the required computations, the TOPSIS method provides a useful, practical tool for analysts and decision-makers with limited technical computational expertise in addressing the warehouse location problem.

Nevertheless, this work is not free from limitations. First, the findings in this work, to some extent, are dependent on the case conditions. Thus, these findings may not reflect other cases with different conditions and must be adopted with care. Second, the limited impact of homogeneous knowledge and expertise of experts on the group decision may be anecdotal evidence. A more controlled investigation on such a claim may serve as grounds for future work.

Third, the TOPSIS method works well not only with a considerable number of criteria but also for a significant number of alternatives. Future works may be extended to multiple warehouse location alternatives. Fourth, it is also possible to explore a group decision-making environment where a criterion is evaluated by a decision-maker with a more significant amount of knowledge and expertise. For instance, a criterion for traffic access could be better assessed by a vehicle operator than a CEO. Lastly, other extensions of TOPSIS, such as the use of standard fuzzy sets, hesitant fuzzy sets, type-2 fuzzy sets, neutrosophic sets, and grey theory, under a group decision-making process, could be explored in future work.

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Appendix 1. Comparative analysis of well-known multi-criteria decision-making methodologies (adopted from Özcan et al., 2011)

Characteristics	AHP	TOPSIS	ELECTRE I	ELECTRE II	ELECTRE III
Core process	Creating hierarchal structure and pairwise comparison matrices	Calculating distance to positive and negative ideal point	Determining concordance and discordance indexes	Determining concordance and discordance indexes	Determining concordance and discordance indexes with indifference and preference thresholds
Necessity to quantify the relative importance of criteria	Yes	Yes	Yes	Yes	Yes
Determining of weights	Pairwise comparison matrices. 1-9 scale	No specific method. Linear or vector normalisation	No specific method. Based on decision maker	No specific method. Based on decision maker	No specific method. Based on the decision maker
Number and type of outranking relations	N*(N-1)/2	1	2	2	1 fuzzy
Consistency check	Provided	None	None	None	Provided
Problem structure	Little number of alternative and criteria or qualitative data	Large number of alternative and criteria, objective and quantitative data	Large number of alternatives and criteria, objective and quantitative data	Large number of alternatives and criteria, objective and quantitative data	Objective and quantitative data, usage of fuzzy logic
Final results	Global, net ordering	Global, net ordering	A kernel	A partial pre-order	A partial pre-order

Appendix 2. Some warehouse location selection criteria

Source	Location selection criteria
Özcan et al. (2011)	unit price; stock holding capacity; average distance to main supplier; average distance to shops; movement flexibility
Dey et al. (2017)	availability of markets; transportation facility; space availability; costs
Demirel et al. (2010)	costs; labour characteristics; infrastructure; markets; macro-environment
García et al. (2014)	accessibility to the area; distance; costs; security of the region; local acceptance of the company; company needs
Alberto (2000)	environmental aspects; costs; quality of living; local incentives; time reliability provided to customers; response flexibility to customers' demands; integration with customers
Chan et al. (2007)	cost expected; traffic access; market opportunity; quality of living; local incentives
Dogan (2012)	quality of labour; quality of suppliers; demographics; geographical location; quality of life; financial efficiency; quality of transportation; government efficiency; quality and infrastructure; regulatory; social and cultural factors; economic performance
MacCarthy and Atthirawong (2003)	Costs; labour characteristics; infrastructure; proximity to suppliers; proximity to markets/customers; proximity to parent company's facilities; proximity to competition; quality of life; legal and regulatory framework; economic factors; government and political factors; social and cultural factors; characteristics of a specific location
Roh et al. (2013)	location; logistics; national stability; cost; cooperation
Melachrinoudis and Min (2000)	cost; traffic access; local incentives
Kuo (2011)	port rate; import/export volume; location resistance; extension transportation convenience; trans-shipment time; one-stop service; information abilities; port and warehouse facilities; port operation system; density of shipping line
Rao et al. (2015)	price of acquiring land; upside delivery flexibility; transportation conditions; service level; human resources condition; environmental protection level; impact on ecological landscape; natural conditions; public facilities condition; security; comply with sustainability laws and regulations; impact on nearby residents; impact on traffic congestion
Colson and Dorigo (2004)	surface of storage; volume of storage; general storage; storage of dangerous items; temperature-controlled storage; separated storage areas; heating; humidity-controlled environment; ventilation-controlled environment; insulated roof and walls; office(s) present on site; distance from nearest motorway; connection to rail; connection to waterways; certified to ISO 9001/9002; certified to SQAS; certified to HACCP; daily opening hours; customs on site; bonded warehouse; feigned warehouse; simple inventory recording; real inventory management; use of bar codes or tags; interfaced computer system; RF communications; (Re-)packaging; order management; transport/distribution; only for receipts and issues; mixed with trans-shipment for third parties; forklift trucks-electric; forklift trucks-gas; forklift trucks-diesel/petrol; tractors for terminal; height stacking; open loading/unloading docks; covered loading/unloading docks; dock levellers; automatic docks; and docks for swap bodies/semi-trailers