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Intermodal Terminal Subsystem Technology Selection Using Integrated Fuzzy MCDM Model

Mladen Krstić [1,2,*], Snežana Tadić [1], Valerio Elia [3], Stefania Massari [4] and Muhammad Umar Farooq [5]

[1] Logistics Department, Faculty of Transport and Traffic Engineering, University of Belgrade, VojvodeStepe 305, 11000 Belgrade, Serbia
[2] Department of Biological and Environmental Sciences and Technologies, University of Salento, Via Monteronisnc, 73100 Lecce, Italy
[3] Department of Innovation Engineering, University of Salento, Via per Monteronisnc, 73100 Lecce, Italy
[4] Department of Economic Sciences, University of Salento, Via per Monteronisnc, 73100 Lecce, Italy
[5] Department of Business Studies, Namal University Mianwali, Mianwali 42250, Pakistan
* Correspondence: mladen.krstic@unisalento.it; Tel.: +381-64-192-66-69

Abstract: Intermodal transportation is the use of multiple modes of transportation, which can lead to greater sustainability by reducing environmental impact and traffic congestion and increasing the efficiency of supply chains. One of the preconditions for efficient intermodal transport is the efficient intermodal terminal (IT). ITs allow for the smooth and efficient handling of cargo, thus reducing the time, cost, and environmental impact of transportation. Adequate selection of subsystem technologies can significantly improve the efficiency and productivity of an IT, ultimately leading to cost savings for businesses and a more efficient and sustainable transportation system. Accordingly, this paper aims to establish a framework for the evaluation and selection of appropriate technologies for IT subsystems. To solve the defined problem, an innovative hybrid multi-criteria decision making (MCDM) model, which combines the fuzzy factor relationship (FFARE) and the fuzzy combinative distance-based assessment (FCODAS) methods, is developed in this paper. The FFARE method is used for obtaining criteria weights, while the FCODAS method is used for evaluation and a final ranking of the alternatives. The established framework and the model are tested on a real-life case study, evaluating and selecting the handling technology for a planned IT. The study defines 12 potential variants of handling equipment based on their techno-operational characteristics and evaluates them using 16 criteria. The results indicate that the best handling technology variant is the one that uses a rail-mounted gantry crane for trans-shipment and a reach stacker for horizontal transport and storage. The results also point to the conclusion that instead of choosing equipment for each process separately, it is important to think about the combination of different handling technologies that can work together to complete a series of handling cycle processes. The main contributions of this paper are the development of a new hybrid model and the establishment of a framework for the selection of appropriate IT subsystem technologies along with a set of unique criteria for their evaluation and selection.

Keywords: intermodal transport terminal; handling technology selection; hybrid MCDM; fuzzy FARE; fuzzy CODAS; integrated FFARE–FCODAS

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1. Introduction

Global changes such as globalization, economic and demographic shifts, technological advancements, and environmental concerns create complex challenges in the field of transportation and logistics. These challenges involve meeting high expectations, using advanced technologies, and achieving sustainable development goals [1]. To address these requirements, the widespread use of intermodal transportation is crucial, and the proper planning and development of intermodal terminals (ITs) are essential for connecting different modes of transportation and technologies [2,3]. Intermodal transportation involves the "*movement of goods in one and the same loading unit or vehicle which uses successively several modes of transport without handling of the goods themselves in changing modes*" [4]. The goal is to combine different modes of transportation to reduce costs and improve service quality [5]. Intermodal transport leads to greater sustainability by reducing the environmental impact of transportation. For example, using trains to transport cargo over long distances can reduce the number of trucks on the road, which can decrease air pollution and traffic congestion. Additionally, intermodal transportation can also increase the efficiency of supply chains, which can reduce the overall amounts of resources required to transport goods. Overall, intermodal transportation can play an important role in promoting sustainable transportation practices. ITs are a key component of intermodal transportation and represent a "place equipped for the transhipment and storage of intermodal transport units (ITUs) between modes" [6]. ITs are important for socio-economic and environmental sustainability and contribute to market competitiveness, making them the the subject of various studies, including the optimization and design of terminal components, berth scheduling, evaluating logistical performance for transport mode selection, measuring terminal performance, analyzing the terminal market and stakeholders, modelling operations, and addressing container disposal issues, layout optimization, and terminal location [7]. ITs can have various subsystems, some of which are routing and scheduling, yard management, gate control, tracking and monitoring, automation and robotics, security, etc. The proper design of ITs greatly depends on the subsystems' technologies, which implies various solutions and equipment that are used within them to perform or facilitate various processes. Accordingly, the aim of this paper is the evaluation and selection of appropriate IT subsystem technologies. The most essential subsystem is the ITU handling subsystem whose goal is to optimize different processes such as container handling, stacking, and movement, with the help of various handling equipment (HE). Accordingly, the subject of this paper is a selection of the appropriate handling technologies that have one of the key roles in achieving IT efficiency in general.

Defining handling technology in this paper implies the selection of one of the possible variants of handling equipment (HE) combinations for the realization of three basic processes of the handling cycle: trans-shipment of intermodal transport units (ITU), horizontal transport, and storing of ITUs. Trans-shipment means unloading/loading full or empty ITUs from/onto the transport means and their servicing in the HE operation area. Storing refers to the processes of capturing and depositing ITUs in the yards for storage of full and empty ITUs. In general, these processes can be physically realized in the same space, or they can be separated, which depends on the type and size of the terminal. If they are separated, horizontal transport is primarily used to connect the places where these processes, but also many others, are carried out, such as ITU filling, emptying, cleaning, servicing, maintaining, repairing, etc. Accordingly, the goal of the paper is to determine the most suitable combination of handling equipment (HE) for a set of basic handling processes in an IT, considering various factors. The defined problem is discussed through the case study of selecting the HE for the planned IT in Belgrade. For solving the defined problem, an innovative multi-criteria decision-making (MCDM) model that combines the fuzzy factor relationship (FFARE) method and the fuzzy combinative distance-based assessment (FCODAS) method is developed in the paper. The results of the case study indicate that instead of choosing equipment for each process separately, it is important to think about the combination of different handling technologies that can work together to complete a series of handling cycle processes. The main contributions of the paper are the establishment of unique HE combinations for medium-to-large-sized ITs, as well as the innovative hybrid MCDM model for evaluating and selecting the most applicable combination in a given circumstance.

The paper is organized as follows: Section 2 provides an overview of the papers covering problems related to intermodal terminal handling technologies and methods for selecting them, with a focus on the hybrid MCDM models. Section 3 provides a detailed description of the newly developed MCDM model and its application steps. Section 4 describes the application of the model and presents the results and sensitivity analysis. Section 5 discusses the obtained results and the applicability of the model. The final section offers conclusions and future research directions.

2. Literature Review

As the nodes in the networks that are used as a connection (interface) between the different modes of transport, ITs represent one of the basic elements of the intermodal transport system [8]. They can appear in different forms [9,10] and have different dimensions [11], layouts [12], structures of functions and subsystems [13], services [14], etc. However, subsystem technologies, primarily handling technologies, have a major role in achieving the efficiency of ITs [13], which is why they are often the subject of research in the literature. Some of the researched problems related to the handling technologies are assigning the HE to tasks (e.g., [15]), routing of HE (e.g., [16]), performance analysis of the handling technologies (e.g., [17]), comparison of conventional and autonomous handling technologies (e.g., [18]), functioning of technologies to minimize the handling cycle (e.g., [19]), defining terminal capacities based on selected handling technology (e.g., [20]), etc.

One of the problems that attracts a lot of attention is the selection of adequate handling technologies. In the literature, this problem is mainly seen as a problem of ranking and selection of the individual HE that implements some of the basic processes of the handling cycle, such as trans-shipment of ITUs, horizontal transport, and storing of ITUs. Some of the HE types that have been considered and evaluated in previous research on their application to implementing the mentioned processes are rubber-tired gantry crane (RTG), rail-mounted gantry crane (RMG), straddle carrier (SC), reach stacker (RS), front-lift tractor (FLT), self-loading trailer (SLT), side loader (SL), automated guided vehicle (AGV), automated lifting vehicle (ALV), and automated straddle carrier (ASC). An overview of this research and the considered HE types is given in Table 1. The authors have not considered a wide set of HE types for the implementation of the mentioned processes. Moreover, most authors considered only up to three types of HE. Additionally, no one has considered, compared, and evaluated certain types of HE such as truck–trailer (TT), multi-trailer system (MTS), overhead bridge crane (OHB), ship-to-shore crane (SS), quay crane (QC), and mobile harbor crane (MH), against the mentioned types of HE. In addition, some authors compared HE types with different dominant functions and even HE that is mutually non-comparable because it cannot realize the same functions (e.g., SC that cannot trans-ship ITUs from the vessels and RMG). Last but not least, no one took into account that none of the HE types can independently implement all processes. So far, possible combinations of HE types that can realize the entire handling cycle have not been considered and ranked. These are the main research gaps that this paper tries to cover.

Table 1. Overview of the considered HE types for IT operations in the literature.

	RTG	RMG	SC	RS	FLT	SLT	SL	AGV	ALV	ASC
[5]			✓	✓	✓	✓	✓			
[21]	✓	✓		✓						
[22]			✓							✓
[23]	✓	✓	✓							
[24]	✓	✓	✓	✓						
[25]	✓	✓	✓	✓	✓			✓	✓	
[26]								✓	✓	
[27]										✓
[28]				✓						

The techniques of optimization or mathematical modelling (e.g., [23,29]), simulation (e.g., [22]), and different MCDM [30,31] are most often used in the literature for selection of HE (e.g., [5,21,24,32,33]). There are also examples of the combination of the aforementioned approaches (e.g., [34]). In this paper, an innovative hybrid MCDM model which combines the fuzzy FARE (FFARE) and the fuzzy CODAS (FCODAS) methods are developed for selecting the handling technology for the planned IT.

The creator of the FARE method is Ginevicius [35]. It implies defining the relationship between all elements involved in decision making (criteria, sub-criteria). Initially, experts provide a very small amount of data (evaluations) on the existence, direction, and strength of influences between individual decision-making elements [36]. These evaluations are entered in the first row of the comparison matrix and used in later phases to analytically determine the impact among other elements of decision making. This significantly reduces the number of expert evaluations needed [37]. The comparison matrix is completely consistent and does not need to be revised, which ensures the results of the applying method are more reliable and stable [37,38]. These advantages were crucial for the FARE method's being chosen for the evaluation and determination of criteria weights in this paper. Since the method is based on decision makers' (DMs') opinions, which take into consideration subjective and uncertain information, the use of fuzzy logic is highly recommended. It allows for the representation of this uncertainty and subjectivity in the evaluation process by using linguistic variables and fuzzy sets to represent imprecise or vague information. An extension of the FARE method using fuzzy logic, developed by Roy et al. [39], was used in the paper. FARE has been widely applied in various fields. Although the method can be applied alone, it is more often used as part of hybrid MCDM models combining multiple methods. Using this method along with other methods, Roy et al. [39] evaluated and selected a logistics service provider; Yazdani [40] selected production materials; Chatterjee et al. [37] selected a machining process; Stankevičienė et al. [41] assessed the impact of technology transfer on created value; Pitchipoo et al. [42] evaluated visibility in freight vehicles; Krstić et al. [43] evaluated sustainable last-mile solutions; Kazan et al. [38] selected political candidates; Girdzijauskaite et al. [44] evaluated the impact of key performance indicators on university competitiveness; etc.

The creators of the CODAS method are Ghorabaee et al. [45]. It belongs to the group of distance-based methods. Such methods are particularly suitable for larger problems, such as the one discussed in this paper, because they require much fewer comparisons than the pairwise methods, such as AHP (analytical hierarchy process) [46], ANP (analytical network process), BWM (best–worst method) [47], etc. The method uses Euclidean and taxicab distance measurements from the negative ideal solution for ranking the alternatives [45]. Euclidean distances are used for the primary evaluation of the alternatives. In the case of close values of these distances for the two alternatives, the additional distinction is made by using the taxicab distances. The advantage of this method over other methods from this group, such as TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution), VIKOR (VIšekriterijumsko KOmpromisno Rangiranje), EDAS (Evaluation Based on Distance from Average Solution), COPRAS (COmplex PRoportional ASsessment), etc., is the possibility of including more than one distance measure in the evaluation process. In this way, the accuracy of the ranking results is significantly increased and a fine differentiation between closely ranked alternatives is enabled [45]. The flaw of the conventional CODAS method is the potential ambiguity of the DMs when defining the preferences. As in the case of the FARE method, this can be solved by applying fuzzy logic. A fuzzy extension of the CODAS method is performed by Ghorabaee et al. [48]. Although it is a relatively new method, it has found a very wide application in a very short time. In its conventional form or its fuzzy extension, independently or as part of a hybrid model, CODAS was used for 3PL (3rd Party Logistics) provider selection [49], the establishment of smart city solutions [50], supplier selection [51], personnel evaluation [52], facility location [53,54], most polluted cities ranking [55], vehicle selection [56], etc. However, the CODAS method has never been used in any form for the selection of handling technology in ITs, which is another research gap this paper is trying to cover.

FFARE and FCODAS methods are already well-established and broadly used MCDM methods. However, in recent years, in the field of MCDM theory, there is a trend of developing hybrid models that combine two or more methods. It is proven that a DM or a group of DMs can be more confident in the results when hybrid MCDM is applied, especially in cases of increasing variety and complexity of information as well as when facing more challenging problems [57]. Accordingly, another significant research gap that this paper covers is the development of a new hybrid MCDM model that combines the FFARE and FCODAS methods.

3. Proposed Hybrid FFARE—FCODAS MCDM Model

An innovative hybrid MCDM model proposed in this paper integrates the FFARE and the FCODAS methods into a single hybrid model. The FFARE method is used in the model for the evaluation and determination of the criterion weights, while the FCODAS method is used for the evaluation, ranking, and selection of the most favorable alternative according to the defined criteria. The overview of the model is presented in Figure 1. The following describes in detail the steps of the proposed model.

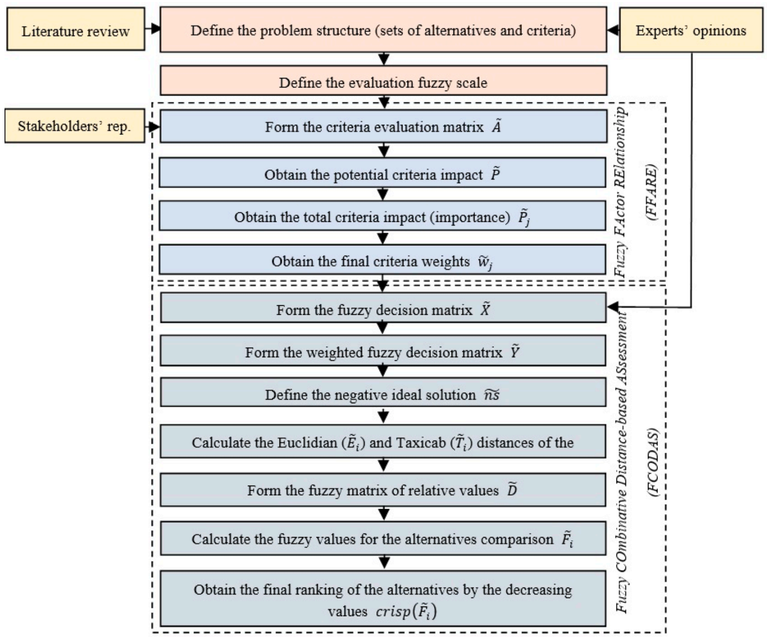

Figure 1. General concept of the proposed hybrid MCDM model.

Step 1: Define the problem structure. Establish the sets of alternatives and criteria for their evaluation.

Step 2: Define the fuzzy scale for the evaluation. Criteria and alternatives are evaluated by the DMs using linguistic terms which can be transformed into triangular fuzzy numbers (TFNs) using the relations given in Table 2.

Table 2. Fuzzy scale for the evaluation.

Linguistic Term	Abbreviation	Fuzzy Scale
"None"	"N"	(1, 1, 2)
"Very low"	"VL"	(1, 2, 3)
"Low"	"L"	(2, 3, 4)
"Fairly low"	"FL"	(3, 4, 5)
"Medium"	"M"	(4, 5, 6)
"Fairly high"	"FH"	(5, 6, 7)
"High"	"H"	(6, 7, 8)
"Very high"	"VH"	(7, 8, 9)
"Extremely high"	"EH"	(8, 9, 10)

Step 3: Obtain the criteria weights. The FFARE method (adapted from Ref. [39]) is used for obtaining the criteria weights. More detailed steps are as follows:

Step 3.1: Form the criteria evaluation matrix $\widetilde{A}$. Linguistic evaluations by the DMs are transformed into TFNs using the relations from the Table 2,

$$\widetilde{A} = [\widetilde{a}_{ij}]_{n\times n}, \quad (1)$$

where $\widetilde{a}_{ij} = (l,\ m,\ u)$ is the evaluation of the importance of the criterion i in relation to the criterion j. Items l, m and u are lower, middle, and upper values of the TFNs $\widetilde{a}_{ij}$.Item n is the number of criteria taken into account. When forming the matrix $\widetilde{A}$, the following applies:

$$\widetilde{a}_{ji} = -\widetilde{a}_{ij}, \quad (2)$$

and the evaluation is considered consistent if:

$$\sum\nolimits_{j=1}^{n} u = -\sum\nolimits_{j=1}^{n} l, \quad (3)$$

Step 3.2: Obtain the potential criteria impact $\widetilde{P}$ as

$$\widetilde{P} = \widetilde{H}(n-1), \quad (4)$$

where $\widetilde{H}$ is the highest value of the scale used for the evaluations.

Step 3.3: Obtain the total impact (importance) of criterion $\widetilde{P}_j$ as

$$\widetilde{P}_j = \sum\nolimits_{i=1}^{n} \widetilde{a}_{ij},\ \forall j = 1,\ldots,n,\ j \neq i, \quad (5)$$

Step 3.4: Obtain the final fuzzy criteria weights $\widetilde{w}_j$ as

$$\widetilde{w}_j = \widetilde{P}_j^r / \widetilde{P}_H,\ \forall j = 1,\ldots,n, \quad (6)$$

where $\widetilde{P}_H$ is the total potential impact (importance) of criteria obtained as

$$\widetilde{P}_H = (\min_j l^{\widetilde{P}_j^r}, \operatorname*{mean}_j m^{\widetilde{P}_j^r}, \max_j u^{\widetilde{P}_j^r}), \quad (7)$$

and $\widetilde{P}_j^r$ is the real total impact of the criterion j obtained as:

$$\widetilde{P}_j^r = \widetilde{P}_j + \widetilde{P},\ \forall j = 1,\ldots,n, \quad (8)$$

Step 4: Evaluate the variants. The FCODAS method is used to evaluate and rank the alternatives (variants). Application steps are obtained by extending the conventional CODAS [45] method into the fuzzy environment.

Step 4.1: Generate the fuzzy decision matrix as

$$\widetilde{X} = [\widetilde{x}_{ij}]_{n\times m} = \begin{bmatrix} \widetilde{x}_{11} & \widetilde{x}_{12} & \cdots & \widetilde{x}_{1m} \\ \widetilde{x}_{21} & \widetilde{x}_{22} & \cdots & \widetilde{x}_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \widetilde{x}_{n1} & \widetilde{x}_{n2} & \cdots & \widetilde{x}_{nm} \end{bmatrix}, \quad (9)$$

where $\widetilde{x}_{ij} = \left(l_{ij}^{\widetilde{x}}, m_{ij}^{\widetilde{x}}, u_{ij}^{\widetilde{x}}\right)$ denotes the TFN of alternative i (i = 1, 2, … , n) in relation to the criterion j (j = 1, 2, … , m), while $l_{ij}^{\widetilde{x}}$, $m_{ij}^{\widetilde{x}}$, and $u_{ij}^{\widetilde{x}}$ denote lower, middle and upper values of the TFN $\widetilde{x}$ respectively, which corresponds to the linguistic evaluations from Table 2.

Step 4.2: Form the weighted fuzzy decision matrix ($\widetilde{Y}$) as

$$\widetilde{Y} = [\widetilde{y}_{ij}]_{n\times m}, \quad (10)$$

$$\widetilde{y}_{ij} = \widetilde{w}_j \otimes \widetilde{x}_{ij}, \tag{11}$$

where $\widetilde{w}_j$ denotes the TFN indicating the weight of the criterion j.

Step 4.3: Define the negative ideal solution ($\widetilde{ns}$) as

$$\widetilde{ns} = \left[\widetilde{ns}_j\right]_{1\times m}, \tag{12}$$

$$\widetilde{ns}_j = \left(\min_i l_{ij}^{\widetilde{y}},\ \min_i m_{ij}^{\widetilde{y}},\ \min_i u_{ij}^{\widetilde{y}} \right), \tag{13}$$

where $l_{ij}^{\widetilde{y}}$, m_{ij}^{y}, and u_{ij}^{y} indicate the lower, middle and upper values of the TFN $\widetilde{y}$, respectively.

Step 4.4: Obtain the fuzzy Euclidian and fuzzy taxicab distances of the alternatives from the negative ideal solution as

$$\widetilde{E}_i = \left(\sqrt{\sum_{j=1}^{m} \left(l_{ij}^{\widetilde{y}} - u_j^{\widetilde{ns}} \right)^2}, \sqrt{\sum_{j=1}^{m} \left(m_{ij}^{\widetilde{y}} - m_j^{\widetilde{ns}} \right)^2}, \sqrt{\sum_{j=1}^{m} \left(u_{ij}^{\widetilde{y}} - l_j^{\widetilde{ns}} \right)^2} \right), \tag{14}$$

$$\widetilde{T}_i = \left(\sum_{j=1}^{m} \left| l_{ij}^{\widetilde{y}} - u_j^{\widetilde{ns}} \right|, \sum_{j=1}^{m} \left| m_{ij}^{\widetilde{y}} - m_j^{\widetilde{ns}} \right|, \sum_{j=1}^{m} \left| u_{ij}^{\widetilde{y}} - l_j^{\widetilde{ns}} \right| \right), \tag{15}$$

where $l_{ij}^{\widetilde{ns}}$, $m_{ij}^{\widetilde{ns}}$, and $u_{ij}^{\widetilde{ns}}$ indicate the lower, middle and upper values of the TFN $\widetilde{ns}$, respectively.

Step 4.5: Generate the fuzzy matrix of alternative distances from the $\widetilde{ns}$ negative ideal as:

$$\widetilde{D} = \left[\widetilde{d}_{ik}\right]_{n\times n}, \tag{16}$$

$$\widetilde{d}_{ik} = \left(\widetilde{E}_i - \widetilde{E}_k \right) + \left(\psi\left(\widetilde{E}_i - \widetilde{E}_k \right) \times \left(\widetilde{T}_i - \widetilde{T}_k \right) \right), \tag{17}$$

where d_{ik} denotes the distance of the alternative from the negative ideal solution, which takes into consideration the Euclidian and the taxicab distances, k = 1, 2, . . . , n is the index of the alternative, and ψ denotes a threshold function to recognize the equality of the Euclidean distances of two alternatives, and is defined as

$$\psi_{ik} = \begin{cases} 1\ if \left| crisp\left(\widetilde{E}_i\right) - crisp\left(\widetilde{E}_k\right) \right| \geq \tau \\ 0\ if \left| crisp\left(\widetilde{E}_i\right) - crisp\left(\widetilde{E}_k\right) \right| < \tau \end{cases}, \tag{18}$$

where crisp($\widetilde{E}$) denotes the defuzzyfied value of the fuzzy value $\widetilde{E}$ obtained as in [58], according to the following:

$$Crisp\left(\widetilde{E}\right) = \left(l^{\widetilde{E}} + 4 \times m^{\widetilde{E}} + u^{\widetilde{E}} \right)/6, \tag{19}$$

In Equation (13), τ denotes the threshold parameter. The DMs define this parameter, and it is recommended that it be a value from the interval (0.1, 0.5). The parameter states that if the difference between the Euclidean distances of two alternatives exceeds τ, then the taxicab distance will also be considered when comparing the alternatives.

Step 4.6: Obtain the fuzzy values for the alternatives comparison as in [45], according to the following:

$$\widetilde{F}_i = \underset{k}{mean} \widetilde{d}_{ik}, \tag{20}$$

Step 4.7: Obtain the final ranking of the alternatives by arranging the crisp ($\widetilde{F}_i$) values, obtained by Equation (14), in decreasing order.

4. Case Study—Handling Technology Selection

There are various criteria for the classification of ITs, such as place and function in the logistics network, size, etc. [59], but for the selection of handling technology, the most important classification is based on the connection between modes of transport and the intensity of flows [5]. The proposed MCDM model is used for the selection of the handling technology in the second stage of development of the planned road–rail terminal in Belgrade. The terminal development is planned in several stages, the first of which would involve one or two trans-shipment tracks and a turnover of about 80,000 ITUs/year [60]. The selection of HE for the first stage of IT development is discussed in the paper by Krstić et al. [5]. The second stage of IT development would involve a capacity of about 200,000 ITUs per year and four or five trans-shipment tracks [60]. Defining the handling technology for this phase of the terminal development implies the selection of one of the possible variants of the HE combination for the realization of the processes of ITU trans-shipment, horizontal transport, and ITU storing.

The first step in handling technology selection involves defining the potential HE for each of the basic processes of the handling cycle. This largely depends on the dominant function that the HE performs, based on which it can be classified as equipment with dominant horizontal or dominant vertical action. Equipment that performs primarily horizontal activities is used exclusively for the internal transport between the subsystems in the terminal, while equipment with dominant vertical action is mainly used for the ITU trans-shipment and storing processes. Equipment with a dominant horizontal action can be further classified as active, which can independently capture and dispose of an ITU, and passive, which does not have this option and requires the assistance of equipment with a dominant vertical action when capturing and disposing of an ITU. The most commonly used active HE types with a dominant horizontal action are SC and SLT, while the passive ones are AGV, TT, and MTS. Concerning equipment with a dominant vertical action, the most commonly used are FLT, RS, SL, RMG, OHB, RTG, SS or QC, MH, etc. [61,62]. Of all the mentioned equipment, SS and MH are used for the trans-shipment of maritime and river vessels, and they will not be considered further, because the planned terminal in Belgrade is bimodal. In road–rail terminals, RS, SC, FLT, SL, RTG, RMG, and TT (only for road vehicles) can be used for trans-shipment, RS, SC, FLT, SL, SLT, TT, MTS, and AGV for horizontal transport, and RS, SC, FLT, SL, RTG, RMG, and OHB for storing processes [6]. It can be noticed that certain HE can independently perform each of these processes, but it is important to consider the justification for their use in terms of the techno-operational characteristics and the expected scope of work when defining the variants. From the possible HE, RTG and RMG are selected as the potential ones for the realization of trans-shipment in the planned terminal. RS, SC, FLT, and SL are not selected, because their capacity does not meet the requirements of the expected throughput of the terminal. This does not mean that some of this HE, if present in the terminal, cannot be used to perform this process. If necessary, it can be used as a secondary (auxiliary) means. RS and SC are selected as potential equipment for the realization of storing processes. As a significant number of planned ITUs will be briefly stored in the terminal, in the operating area of the trans-shipment cranes, the expected operating scope does not justify the introduction of high-capacity equipment, such as RTG, RMG, or OHB, for performing the storing processes in the storage yards for full and empty ITUs. On the other hand, FLT and SL are rarely used for the realization of these processes due to small lifting heights. RS, SC, SLT, and TT are selected as potential HE for the realization of horizontal transport. FLT and SL are rarely used for this process, since they are slow. MTS has very similar techno-operational characteristics to TT. However, although it has a larger capacity than TT, it is significantly more expensive and requires much more manipulative surfaces, so its application in the planned terminal is not justified. AGV is not selected as a potential asset because it generates high procurement and maintenance costs that could not be justified by the expected operational scope of the planned terminal.

The second step is to define the variants by combining the potential HE for the realization of the basic processes of the handling cycle. By defining all possible combinations of potential HE, 16 variants are obtained. However, four variants that involve the use of both RS and SC for horizontal transport, i.e., storing processes, have been eliminated, because there is no need to introduce additional HE for processes that can be performed by one HE. For example, if it is defined that HE performs horizontal transport, it does not make sense to introduce SC to perform storing processes, because RS can perform this process as well. In this way, 12 variants shown in Table 3 are obtained and taken into further consideration.

Table 3. Variants of the handling technologies.

Variant	Process		
	Trans-Shipment	**Horizontal Transport**	**Storing**
V_1	RTG	RS	RS
V_2	RTG	SC	SC
V_3	RTG	SLT	RS
V_4	RTG	SLT	SC
V_5	RTG	TT	RS
V_6	RTG	TT	SC
V_7	RMG	RS	RS
V_8	RMG	SC	SC
V_9	RMG	SLT	RS
V_{10}	RMG	SLT	SC
V_{11}	RMG	TT	RS
V_{12}	RMG	TT	SC

In the third step of the process, the variants are evaluated based on 16 criteria that are divided into three categories: technical, economic, and technological. The technical criteria include productivity (C_1), which implies the number of ITUs that the system can serve in a certain period, and is mostly determined by the HE that performs the ITU trans-shipment process; load capacity (C_2) of HE used in the system, which implies the maximum allowable load when handling a single ITU; the speed of movement (C_3) of loaded or unloaded HE in the system, primarily HE for the realization of the horizontal transport; lifting height (C_4) to which HE can lift the ITUs, primarily HE for performing the storing processes; required surfaces (C_5) that depend on the required space for handling the loaded or unloaded HE, the width of working aisles and the necessity of their existence, the width of internal roads and turning radii, etc. The economic criteria include purchase price (C_6), which implies the investment costs necessary for the purchase of HE used in the system; maintenance costs (C_7), which include costs of the HE maintenance, repairs, servicing, etc.; lifetime (C_8) relating to the expected period of use of the HE in the IT system depending on the utilization rate and working environment; operating costs (C_9), which include the costs of energy consumption, labor, preparation for work, etc. of the HE used in the system; terminal design costs (C_{10}), which include the costs of planning, preparing and equipping the terminal to work with the selected HE. The group of technological criteria includes mutual compatibility (C_{11}) of the HE used for the realization of different processes of the handling cycle; multi-functionality (C_{12}), which implies the possibility of using the HE for the realization of multiple processes of the handling cycle; interoperability (C_{13}), which implies the possibility of integrating HE into technologies of different terminal subsystems; the complexity of handling processes (C_{14}), that generates the need to plan and organize handling processes before the implementation; the possibility of process automation (C_{15}), i.e., the possibility of using innovative technological solutions that enable a higher level of automation and autonomy in the operation of the HE; required training for operating (C_{16}) considers whether special training and permits are required for the operation with the HE, as well as the duration of the training or licensing, if necessary.

Once the problem is structured, i.e., variants and criteria are defined, the FFARE is applied (Step 3) to obtain the criteria weights. As stated in Step 3.1, the criteria are evaluated with linguistic assessments (Table 4).

Table 4. Linguistic assessments of the criteria.

C_j	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}
C_1	-	“VV”	“N”	“N”	“UN”	-	“S”	“VV”	“V”	“EV”	“VN”	“VN”	“V”	“VV”	“UV”	“EV”
C_2	-	-	-	-	-	-	-	“NI”	-	“VN”	-	-	-	“NI”	-	“VN”
C_3	-	“U”	-	“NI”	“VN”	-	“N”	“UV”	“S”	“V”	-	-	“S”	“UV”	“UN”	“V”
C_4	-	“UV”	-	-	“VN”	-	“N”	“UV”	“S”	“V”	-	-	“S”	“UV”	“UN”	“V”
C_5	-	“S”	-	-	-	-	“VN”	“S”	“UN”	“UV”	-	-	“UN”	“S”	“N”	“UV”
C_6	“NI”	“VV”	“N”	“N”	“UN”	-	“S”	“VV”	“V”	“EV”	“VN”	“VN”	“V”	“VV”	“UV”	“EV”
C_7	-	“UN”	-	-	-	-	-	“UN”	“N”	“S”	-	-	“N”	“UN”	“VN”	“S”
C_8	-	-	-	-	-	-	-	-	-	“VN”	-	-	-	“NI”	-	“VN”
C_9	-	“VN”	-	-	-	-	-	“VN”	-	“N”	-	-	-	“VN”	-	“N”
C_{10}	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	“NI”
C_{11}	-	“V”	“VN”	“VN”	“N”	-	“UN”	“V”	“UV”	“VV”	-	“VN”	“UV”	“V”	“S”	“VV”
C_{12}	-	“V”	“VN”	“VN”	“N”	-	“UN”	“V”	“UV”	“VV”	-	-	“UV”	“V”	“S”	“VV”
C_{13}	-	“VN”	-	-	-	-	-	“VN”	“NI”	“N”	-	-	-	“VN”	-	“N”
C_{14}	-	-	-	-	-	-	-	-	-	“VN”	-	-	-	-	-	“VN”
C_{15}	-	“N”	-	-	-	-	-	“N”	“VN”	“UN”	-	-	“VN”	“N”	-	“UN”
C_{16}	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

The criteria evaluation matrix (1) was formed after the DMs’ linguistic evaluations are transformed into TFNs according to Table 2, while also satisfying conditions (2) and (3). $\widetilde{P}$ was calculated using Equation (4), and $\widetilde{P}_j$ were determined using Equation (5). $\widetilde{w}_j$ were obtained using Equations (6)–(8) and are presented in Table 5.

Table 5. Results of applying FFARE method.

C_j	$\tilde{P}_j$	$\tilde{P}_j^r$	$\widetilde{w}_j$
C_1	(39, 48, 57)	(111, 129, 147)	(0.745, 1.269, 1.995)
C_2	(3.2, 4.6, 7.4)	(75.2, 85.6, 97.4)	(0.505, 0.842, 1.321)
C_3	(24.9, 30.3, 37.5)	(96.9, 111.3, 127.5)	(0.65, 1.095, 1.73)
C_4	(24.4, 30.3, 36.5)	(96.4, 111.3, 126.5)	(0.647, 1.095, 1.717)
C_5	(19.4, 24.9, 31.3)	(91.4, 105.9, 121.3)	(0.613, 1.042, 1.647)
C_6	(40, 49, 59)	(112, 130, 149)	(0.752, 1.279, 2.022)
C_7	(14.1, 19.4, 24.9)	(86.1, 100.4, 114.9)	(0.578, 0.987, 1.559)
C_8	(3.7, 5.6, 8.4)	(75.7, 86.6, 98.4)	(0.508, 0.852, 1.335)
C_9	(5.6, 9.4, 13.1)	(77.6, 90.4, 103.1)	(0.521, 0.889, 1.399)
C_{10}	(2.7, 3.2, 5.6)	(74.7, 84.2, 95.6)	(0.501, 0.829, 1.297)
C_{11}	(31.3, 39.5, 48)	(103.3, 120.5, 138)	(0.694, 1.185, 1.873)
C_{12}	(30.7, 38, 46)	(102.7, 119, 136)	(0.689, 1.171, 1.846)
C_{13}	(5.1, 8.4, 12.1)	(77.1, 89.4, 102.1)	(0.517, 0.879, 1.385)
C_{14}	(2.7, 4.6, 6.4)	(74.7, 85.6, 96.4)	(0.502, 0.842, 1.308)
C_{15}	(8.9, 13.1, 17.4)	(80.9, 94.1, 107.4)	(0.543, 0.925, 1.457)
C_{16}	(1.7, 2.2, 3.6)	(73.7, 83.2, 93.6)	(0.495, 0.819, 1.27)

After defining the criteria weights, alternatives, i.e., variants, are ranked in Step 4. The variants are evaluated by the DMs using the linguistic evaluations (Table 6), which are then converted into TFNs using the relations from Table 2, thus forming a fuzzy decision matrix ($\widetilde{X}$) (Step 4.1).

$\widetilde{R}$ is obtained by applying equations (10) and (11) (Step 4.2). Afterward, $\widetilde{ns}$ is defined using Equations (12) and (13) (Step 4.3), and the $\widetilde{E}_i$ and $\widetilde{T}_i$ are calculated using Equations (14) and (15) (Step 4.4). $\widetilde{D}$ is formed by applying Equations (16)–(18) (Step 4.5), with the parameter τ set to 0.2. Using Equation (20) and the values from the matrix, the $\widetilde{H}_i$ values are obtained (Step 4.6). These values are defuzzyfied by applying Equation (19), and the final ranking of the alternatives is obtained by arranging them in decreasing order (Step 4.7). All these intermediate values, as well as the values based on which the final ranking of the variants was obtained, are presented in Table 7.

Table 6. Variants evaluations in relation to the criteria.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}
V_1	“H”	“H”	“M”	“H”	“VH”	“EH”	“M”	“VH”	“H”	“H”	“VH”	“EH”	“VH”	“H”	“FH”	“EH”
V_2	“VH”	“VH”	“M”	“FH”	“VH”	“VH”	“H”	“FH”	“VH”	“VH”	“FH”	“EH”	“FH”	“VH”	“VH”	“VH”
V_3	“VL”	“FL”	“FH”	“M”	“FH”	“M”	“VL”	“VH”	“M”	“H”	“FL”	“FH”	“M”	“M”	“FL”	“M”
V_4	“L”	“M”	“H”	“FL”	“FH”	“FL”	“FL”	“FH”	“FH”	“VH”	“L”	“FH”	“FL”	“FH”	“M”	“FL”
V_5	“FL”	“FL”	“FH”	“L”	“FH”	“FH”	“VL”	“VH”	“M”	“H”	“VL”	“FL”	“M”	“M”	“FL”	“M”
V_6	“M”	“M”	“H”	“VL”	“FH”	“M”	“FL”	“FH”	“FH”	“VH”	“N”	“FL”	“FL”	“FH”	“M”	“FL”
V_7	“VH”	“VH”	“FH”	“EH”	“EH”	“VH”	“FH”	“EH”	“VH”	“VH”	“EH”	“EH”	“EH”	“FH”	“H”	“VH”
V_8	“EH”	“EH”	“FH”	“VH”	“EH”	“H”	“VH”	“H”	“EH”	“EH”	“H”	“EH”	“H”	“H”	“EH”	“H”
V_9	“L”	“M”	“H”	“H”	“H”	“FL”	“L”	“EH”	“FH”	“VH”	“M”	“FH”	“FH”	“FL”	“M”	“FH”
V_{10}	“FL”	“FH”	“VH”	“FH”	“H”	“L”	“M”	“H”	“H”	“EH”	“FL”	“FH”	“M”	“M”	“FH”	“M”
V_{11}	“M”	“M”	“H”	“FL”	“H”	“M”	“L”	“EH”	“FH”	“VH”	“L”	“FL”	“FH”	“FL”	“M”	“FH”
V_{12}	“FH”	“FH”	“VH”	“L”	“H”	“FL”	“M”	“H”	“H”	“EH”	“VL”	“FL”	“M”	“M”	“FH”	“M”

Table 7. Results of the MCDM model application.

V_j	$\tilde{E}_i$	$\tilde{T}_i$	$\tilde{H}_i$	*Crisp* $(\tilde{H}_i)$	**Rank**
V_1	(17.9, 17.2, 47.6)	(62.9, 56.7, 182.5)	(−96, 28, 126)	35.0	3
V_2	(17.7, 16.6, 47)	(61, 56.2, 181.7)	(−98, 27, 125)	28.6	4
V_3	(22, 6.5, 31.2)	(84, 17.1, 120.3)	(−78, −22, 55)	−17.1	10
V_4	(21.6, 5.8, 31.4)	(83, 18.8, 122.9)	(−76, −22, 54)	−20.7	9
V_5	(22.3, 5.5, 30.1)	(85.8, 14, 115.4)	(−76, −26, 49)	−14.9	12
V_6	(21.9, 6, 30.9)	(84.1, 15.7, 118.1)	(−75, −24, 49)	−16.7	11
V_7	(16.7, 19.4, 51.4)	(58.4, 66.7, 198.4)	(−100, 40, 144)	36.4	1
V_8	(16.6, 18.8, 50.8)	(55.9, 66.2, 197.5)	(−103, 39, 143)	31.4	2
V_9	(20.5, 9.1, 35.7)	(77.1, 28.8, 138.6)	(−79, −8, 70)	−16.0	6
V_{10}	(20.2, 8.9, 36.1)	(76.1, 30.5, 141.3)	(−80, −7, 73)	−16.9	5
V_{11}	(20.8, 7.3, 33.9)	(79.6, 24.6, 132)	(−82, −14, 68)	−14.3	8
V_{12}	(20.6, 8.1, 34.9)	(78.5, 26.3, 134.7)	(−83, −11, 71)	−14.9	7

The results of applying the proposed MCDM model indicate that the best handling-technology variant is the one that uses RMG for trans-shipment and RS for horizontal transport and storage (V_7). The lowest-ranked variant is V_4, which combines the use of RTG, SLT, and SC for trans-shipment, horizontal transport, and storage, respectively. To validate the obtained results, the problem with the same input values was solved with several more MCDM methods, namely the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [63], VIšeKriterijumska Optimizacija I Kompromisno Rešenje (VIKOR) [64], Evaluation based on Distance from Average Solution (EDAS) [65], Multi-Objective Optimization by Ratio Analysis (MOORA) [66], Weighted Aggregated Sum-Product Assessment (WASPAS) [67], Measurement of Alternatives and Ranking according to Compromise Solution (MARCOS) [68], and COmprehensive Distance Based Ranking (COBRA) [69]. The obtained rankings are presented in Table 8. To check if the similarity of the obtained rankings is statistically significant, Spearman correlation coefficient (SCC) was calculated for all pairs of results that the CODAS method makes with each of the other methods. The average SCC is 0.923 which implies that the obtained results have a high degree of conformity with the results obtained with other methods.

To test the stability of these results, a sensitivity analysis was conducted using seven scenarios. In the first scenario (Sc.1), all criteria weights were equalized. In the remaining six scenarios, one of the six most important criteria was excluded, with Sc.2 neglecting C_6, Sc.3 neglecting C_1, Sc.4 neglecting C_{11}, Sc.5 neglecting C_{12}, Sc.6 neglecting C_3, and Sc.7 neglecting C_4. The results of these scenarios were compared to the results obtained by applying the defined model (Sc.0) and are shown in Figure 2. The rankings of the alternatives do not change significantly in any of the scenarios, indicating that the results are stable and can be adopted as the final result.

Table 8. Validation of results.

	CODAS	TOPSIS	VIKOR	EDAS	MOORA	WASPAS	MARCOS	COBRA
V_1	2	2	2	3	2	2	2	2
V_2	4	3	3	4	4	4	4	4
V_3	11	10	8	10	10	10	10	10
V_4	12	12	11	12	12	11	12	12
V_5	6	5	5	9	9	9	9	5
V_6	9	8	7	11	11	12	11	8
V_7	1	1	1	1	1	1	1	1
V_8	3	4	4	2	3	3	3	3
V_9	8	9	9	6	6	6	6	9
V_{10}	10	11	12	7	8	7	8	11
V_{11}	5	6	6	5	5	5	5	6
V_{12}	7	7	10	8	7	8	7	7

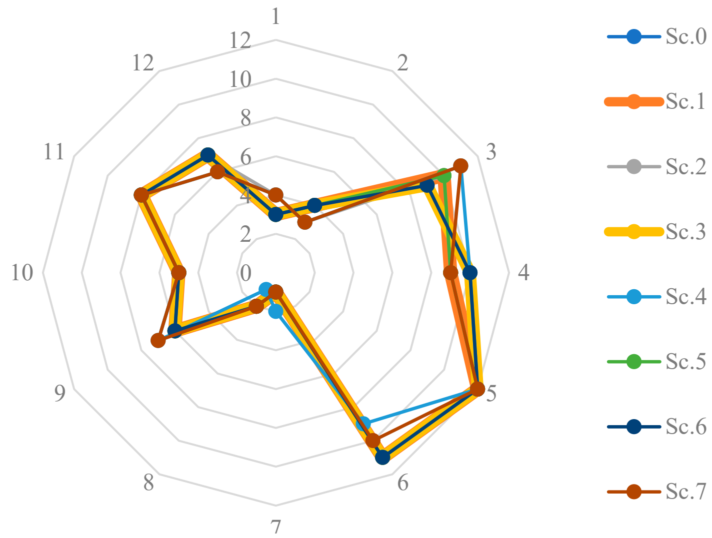

Figure 2. Results of the sensitivity analysis.

5. Results and Discussion

V_7, which implies a combination of RMG and RS, is selected as the most favorable solution to the problem of selecting the handling technology for the second stage of the IT development in Belgrade, with a value of 36.4. Although concerning the two most significant criteria, the purchase price (C_6) and productivity (C_1), this variant is not the best solution and requires significant maintenance costs (C_7), it is selected as the most favorable one. The main reason is that this combination of equipment obtained the highest scores in terms of compatibility (C_{11}), multi-functionality (C_{12}), interoperability (C_{13}), lifting height (C_4), required surfaces (C_5), and expected lifetime (C_8). In addition, the equipment used in this variant provides good load capacity (C_2), has a solid speed (C_3), good automation capabilities (C_{15}), acceptable complexity of manipulative procedures (C_{14}), and does not require high operating costs (C_9) and terminal design costs (C_{10}), nor long-term training of operators operating them (C_{16}). In general, variants in which only two HE are used, i.e., variants in which individual equipment is used for the realization of more than one process, are better ranked than variants that use different equipment for each process. This is especially interesting if we take into account that HE performing several operations in these variants, according to their techno-operational characteristics, does not represent the best solution for the realization of individual processes. It can be concluded that when defining handling technologies, it is not possible to independently select equipment for each of the processes of the handling cycle, but it is necessary to comprehensively observe different combinations of equipment that synergistically realize the defined set of processes.

Observed from the aspect of criteria, the good rank of these variants is achieved by lower costs of procurement (C_6), maintenance (C_7), operation (C_9), and terminal design (C_{10}), on the one side, and high scores on compatibility (C_{11}), multi-functionality (C_{12}), and interoperability (C_{13}), on the other.

Since the beginning of the twenty-first century, and especially in recent years, there has been an expansion of hybrid MCDM methods that involve combining two or more individual methods to use the advantages and suppress the disadvantages of each of them, depending on the problem being solved. The MCDM model proposed in this paper contributes to this body of literature. Two methods are usually combined when one method is not capable or appropriate to provide the criteria weights, or when one method requires extensive resources to provide final results (e.g., requires comparisons of all pairs of elements, which might be problematic for the problems of bigger dimensions). The third method is generally introduced when the problem involves multiple stakeholders or interest groups [3]. In this case it becomes the group MCDM problem, and the third method is generally used to aggregate and reconcile the different views and evaluations of multiple decision makers, stakeholders, interest groups, etc. [70]. Since the problem discussed in this paper did not involve multiple stakeholders, it was appropriate to use a two-methods-based hybrid model. The FFARE is selected because it is easy to use, provides fast results, and is highly reliable. It is particularly helpful for tackling large-scale issues because it does not necessitate extensive comparisons and evaluations of elements (criteria and alternatives). The fact that the method is used in a fuzzy environment enables a more realistic consideration of opinions in decision-making. On the other hand, the CODAS method, which bases the evaluation process on two types of distances from a negative ideal solution, allows fine differentiation of the alternatives, thus providing more reliable results. Their combination results in a simple, resource-saving, efficient, effective, and useful model that is able to provide high-quality reliable results with a reasonable use of resources. The model is applicable not only to the problem described in this paper, but also to make other similar decisions. After some adjustments, it could be used for the selection of technologies for different types of ITs and logistics centers. Additionally, the model could be used to solve other decision-making tasks in intermodal transport and logistics, as well as in other areas.

In addition to the newly developed MCDM model, the main contributions of the paper are the establishment of a framework for the selection of the appropriate IT subsystem technologies and a set of unique criteria for the evaluation and selection of HE for the IT handling subsystem.

The defined problem had certain assumptions. The first assumption is that there are no obstacles to the application of any of the HE and that it is available and affordable. The second is that non-standard ITUs that could not be handled by the defined HE types will not appear in the system. There are also several limitations of the study conducted in this paper. The first concerns the number of factors taken into account. However, consideration of additional factors could significantly complicate the decision-making process, as the ability of decision-makers to evaluate options against a wide set of factors would be questioned. Another limitation concerns the case study. It takes into account only one subsystem and only one type of IT. However, the defined framework could, without major problems be adapted for the technology selection of any subsystem (by changing the variants based on the previous analysis of potential technologies) for any type of terminal. The third limitation concerns the hybrid model. The model did not foresee the possibility of considering and unifying the evaluations of different stakeholders, nor the possibility of preselection of a critical set of most influential criteria.

One theoretical implication of this study is the consideration of the entire handling cycle, i.e., the most important processes in it, simultaneously, when selecting the HE. It is clear that the selection of individual pieces of equipment, that are not optimal for each phase of the handling cycle, can lead to making inadequate decisions, which may result in a lower efficiency of the IT and therefore of the entire intermodal transport system. Another theoretical implication is reflected in the development of a new hybrid MCDM model that contributes to decision theory, the field of MCDM, and more specifically the subfield of hybrid MCDM methods. This is a universal model that could be used to solve any MCDM problem, with any set of criteria and alternatives, which will be proven in future studies applying the model. As for the practical (managerial) implications, one is reflected in fact that the results of this study can be used to improve everyday business and IT efficiency through the implementation of the obtained solution. Another is reflected in the creation of an expert system in the form of a hybrid MCDM model that can help planners, designers, and decision makers during the planning, development, reconstruction, or management of ITs. In particular, the developed model could be used for evaluating software or various applicable Industry 4.0 technologies such as the Internet of things, cyber-physical systems, big data, and data mining, autonomous vehicles, cloud computing, etc.

6. Conclusions

Intermodal transportation, which involves the use of multiple modes of transportation (such as trucks, trains, and ships) to move goods and people, can have a positive impact on environmental, economic, and social sustainability. Intermodal transportation can reduce the number of trucks and decrease carbon emissions, increase the efficiency of the transportation system by reducing costs for businesses and consumers, improve access to goods and services in rural and remote areas, and create jobs in the transportation and logistics industries.

ITs play a crucial role in the efficiency of intermodal transportation by allowing for the seamless transfer of goods and passengers between different modes of transportation. Intermodal terminals can be designed and operated in a way that allows for efficient loading and unloading of cargo, minimizing the time and costs associated with transferring goods between different modes of transportation. Additionally, well-designed intermodal terminals can also help to reduce congestion and improve the flow of traffic in the surrounding transportation network. Properly designed and operated ITs can also reduce the overall carbon footprint of transportation. The proper design greatly depends on the subsystem's technologies. They imply various systems and equipment that are used within ITs to facilitate the transfer of cargo between different modes of transportation. These technologies can have a significant impact on the ITs' efficiency by improving the speed, accuracy, and reliability of cargo handling and transportation operations. Therefore, it is clear why the aim of this paper was a selection of the appropriate IT subsystem technology. The paper established the framework and proposed a novel hybrid MCDM model for the evaluation and selection of IT subsystem technologies. They were tested on a real-life case study of selecting the HE variants for a planned IT terminal.

The results indicate that the best-handling technology variant is the one that uses a rail-mounted gantry crane for trans-shipment and a reach stacker for horizontal transport and storage. The case study shows that the defined model is an effective MCDM tool that allows for efficient, quick, and easy problem solving. It also indicates that when defining handling technologies for terminals with a larger volume of flows, it is necessary to consider the combination of different handling technologies that work together to perform a set of handling cycle processes, rather than selecting equipment for each process independently.

The main contributions of the paper are the establishment of a framework for the selection of appropriate IT subsystem technologies, a set of unique criteria for the evaluation and selection of HE for the IT handling subsystem, and a hybrid MCDM model which combines FARE and CODAS methods in a fuzzy environment.

Future research could focus on modifying the problem to include a greater number or changing set of factors that may affect the definition and prioritization of criteria. The model itself could be applied to the selection of handling technologies in other types of terminals or later phases of terminal development, when an even larger volume of flows is anticipated. In addition, it could be used for the evaluation and selection of technologies for any other IT subsystem, in particular for evaluating software or various applicable

Industry 4.0 technologies. It could also be used to solve similar problems in intermodal transport and other fields. Additionally, the model could be extended to include more DMs representing the needs of different stakeholders. In that case, the model could include methods that allow the unification of their evaluations or the creation of a critical set of criteria or factors (such as the Delphi method).

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