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Selection of an international distribution center location: A comparison between stand-alone ANP and DEMATEL-ANP applications

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ABSTRACT

The problem of Distribution Center (DC) strategic location is critical since it impacts the company's overall distribution strategy and enhances supply chain resilience. This paper compares and evaluates five locations in Europe for the possible establishment of an international distribution center. The Analytic Network Process (ANP) and Decision-Making Trial and Evaluation Laboratory (DEMATEL)-Based ANP techniques were applied in the analysis, considering 25 criteria across seven dimensions. This paper aims to provide a decision-making framework for prioritizing distribution center locations in Europe, identifying key criteria, and ranking alternative locations to guide decision making processes for stakeholders and policy makers involved in DC location selection. The results demonstrated that both approaches rank the alternatives similarly, although they assign varying degrees of importance to decision criteria. The research was constrained by a limited number of alternatives and respondents, as well as imprecision in human judgments. Future research will explore additional sustainability and social criteria, more alternative locations, and incorporate fuzziness for a more comprehensive selection of the optimal International Distribution Center (IDC) location.

1. Introduction

Nowadays the global economy is characterized by a fragile post-pandemic recovery and dimmed by the ongoing war in Ukraine. Supply chains are faced with inventory and shipping issues, while inventory centralization and distribution remain a challenge (Gürbüz, Muerza, Marchiori, & Zangiacomi, 2021). To mitigate these problems, and make supply chains more resilient, the definition of the proper location of distribution centers (DCs) is necessary, which has a fundamental impact on the distribution strategy of a company.

International Distribution Centers (IDCs) are used for global logistics operations. Their location is a key factor as it facilitates the optimization of the supply chain, reducing costs and delivery times. The optimal location of the DC can reduce transportation costs and decrease inbound and outbound lead times, which will facilitate inventory control and thus increase the level of service. Several criteria, apart from lead time and cost reduction, must be taken into consideration while determining the optimal location of a DC. The environment, which consists of society, culture, and infrastructure, is of crucial importance for the functionality of the location. The competitive position of a location may be diminished by cultural differences, unavailability of skilled labor, lack of space and facilities, undeveloped infrastructure, as well as unfavorable tax system and custom procedures. In that case, apparently short distances may be less time-efficient than longer distances in an area with better attributes from the point of view of the above-mentioned criteria. Other criteria influencing DC location are political stability and territorial dimensions (Ayadi, Hamani, Kermad, & Benaissa, 2021; Kumar & Anbanandam, 2020), interconnected business activities and network connections (Elevli, 2014), geographical and physical closeness (Erkayman, Gundogar, Akkaya, & Ipek, 2011), regional characteristics and the price of connection to different means of transport (Kampf, Průša, & Savage, 2011), population and handling capacity of seaports (Önden, Acar, & Eldemir, 2018). Due to the heterogeneity in the typology of criteria affecting the decision, Multiple Criteria Decision

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Making (MCDM) methodologies are revealed as a suitable approach to be applied.

Considering that the dimensions/attributes are interdependent, the Analytic Network Process (ANP) is selected as fa tool that addresses decisions involving dependency and feedback. In the context of ANP applications it is assumed that the problem's network structure is known a priori, however the decision maker may encounter difficulty in readily defining this structural framework (Milenković, Val, Lutovac, Bojović, & Knežević, 2021). The second issue is related to the quantification of influence in ANP models. Namely, in ANP, the influence between criteria is quantified by pairwise comparisons in which interdependencies are treated as reciprocal values (Golcuk & Baykasoglu, 2016), which does not correspond to the real situation. Furthermore, even though ANP allows for an assessment of influence and interdependence, it may lead to a lack of understanding on the part of decision makers. Therefore, as an improvement of the ANP approach for the DC location selection problem, DEMATEL (Decision Making trial and evaluation laboratory) has been integrated with ANP as one of the most popular causal dependency models. DEMATEL allows for a better understanding of influences by analyzing elements in cause-and-effect relationships (Ortíz, Felizzola, & Isaza, 2015). In the integrated DEMATEL- ANP (DANP) approach, DEMATEL first assesses the causal relationships of the dimensions/attributes by decomposing them into groups of causes and effects. The derived causal relationships are then used to determine the attribute weights by applying the ANP method. DEMATEL allows the resolution of complex and interdependent problems (Fontela & Gabus, 1976). Meanwhile, ANP is a generalization of AHP (Saaty, 2008) and avoids the limitations related to the interdependence of nodes at different levels of the hierarchy (Saaty & Vargas, 2006).

In this paper, ANP and DNP have been utilized to determine the most optimal location in Europe for an IDC among five regions known for their heavy logistics activity.

DC location approaches have been mainly implemented at regional/country level, e.g. Puška, Štilic, and Stevic (2023), Kumar and Anbanandam (2020), Ayadi et al. (2021); or company case study, e.g. Liang, Verhoeven, Brunelli, and Rezaei (2021), in different applications, e.g. as refugee camps (Abikova, 2020), offshore out-sourcing (Zhou & Xiao, 2019), wind farms (Gigović, Pamučar, Božanić, & Ljubojević, 2017), ammunition depots (Gigović, Pamučar, Bajić, & Milićević, 2016), freight village locations in Turkey (Karaşan & Kahraman, 2019). Nonetheless, as far as current knowledge extends, no study has been devoted to a comprehensive multicriteria analysis for DC location selection at a global level, particularly focusing on the location of an IDC in Europe.

The research gap is identified based on a combination of recognizing contextual challenges (complexity of supply chain dynamics, transportation and logistics challenges, sustainability, and environmental concerns, among others), acknowledging the importance of specific research questions, and undertaking comprehensive analyses to fill gaps in existing literature related to IDC location selection. The research questions (RQ) designed to fill gaps in existing literature are focused on the following inquiries:

- RQ1. Which are the main dimensions/criteria that can be used to evaluate the location of an IDC in Europe?
- RQ2. Is there any difference in the assessment of the problem using ANP and DE-MATEL-ANP in five real locations in Europe?

By addressing these RQs, the paper contributes to the previous literature in three ways. First, the criteria/dimensions that should be considered by stakeholders in the IDC location selection process are identified and, through an assessment of their influences and interrelationships, their relative weights are determined. This RQ implicitly addresses the question of where an IDC should be located in Europe. Second, two multicriteria decision making methods for the location of International Distribution Centers-ANP, and DANP-are used and their performances are compared from the standpoint of IDC location selection. Third, a detailed assessment of five regions with the highest intensity of logistics activities in Europe is included: North-Rhine Westphalia region (Germany), Aragon region (Spain), South Holland region (The Netherlands), Hauts-de-France region (France), and Emilia-Romagna region (Italy).

The rest of the paper is structured as follows. Following the introduction, a comprehensive literature review is presented in Section 2. Section 3 describes the methodology for the identification and selection of the most important criteria, as well as for the selection of the preferred IDC location in Europe, based on the application of the ANP and integrated DEMATEL and ANP approaches. Section 4 contains an analysis of the results, as well as a sensitivity analysis. Section 5 presents a discussion of the results and implications for management. The last section contains concluding remarks and directions for further research.

2. Literature review

The DC location problem has been studied from different perspectives and methodologies. A classification of approaches includes (Okatan, Peker, & Baki, 2019): (i) mathematical modeling; (ii) heuristic-meta-heuristic methods; (iii) MCDM techniques; (iv) fuzzy logic; and (v) qualitative methods. Thus, for example, Li and Zhou (2021) proposed a multi-objective model for determining the location of cold-chain logistics distribution center. Zhang, Chen, She, and Li (2021) developed a bi-level programming model for determining the optimal location of a cold chain distribution center in Wuhan (China) taking into account the total social cost of the logistics system as well as the cost incurred by each logistics user. Dupas, Deschamps, Taniguchi, Qureshi, and Hsu (2023) modeled the problem of optimal location of urban consolidation centers (UCCs) in the city of Bordeaux (France) as a multicommodity network flow problem. The objective of the resulting linear programming model was to select UCCs based on minimal costs and CO_2 emissions of a two-tier distribution system.

Strutynska, Aftanaziv, Strogan, and Ortynska (2018) proposed an optimization model for regional DCs. The location decision considered population density, goods turnover, distance to customers, infrastructure, and transport in the region. Zhen, Sun, Wang, and Zhang (2019) developed a heuristics tabu search algorithm to determine the optimal location and scale of facilities in a closed-loop supply chain network. Zhang and Yin (2017) proposed a genetic algorithm-based method to solve the logistics center (LC) selection problem, where the objective function was set up with the minimum total cost. In addition, an application of qualitative methods to the location problem can be seen in Essaadi, Grabot, and Fénies (2016). Taouktsis and Zikopoulos (2024) proposed a hybrid approach based on Deep Neural Network (DNN) and Farthest Insertion (FI) algorithm to obtain a DC location with minimal aid distribution distance to support humanitarian logistics networks.

MCDM-based research includes the application of different approaches. For instance, Kampf et al. (2011) used the Weighted Sum Approach for the location of public LCs in the Czech Republic. Meanwhile, Meidutė and Raudeliūnienė (2011) based their approach on a three-stage process: identification, assessment, and estimation of external and internal factors of LC location. The complex multicriteria assessment method was used as a decisional tool. Peker, Baki, Tanyas, and Ar (2016) applied the ANP and a Benefits, Opportunities, Costs & Risks (BOCR) analysis in a case study in Trabzon, Turkey. Pamučar, Dorović, Božanić, and Ćirović (2012) developed a Decision-Making Trial and Evaluation Laboratory – Multi Attributive Ideal-Real Comparative Analysis (DEMATEL-MAIRCA) model for locating a multimodal LC by the Danube River. Liang et al. (2021) applied the best-worst method (BWM) for the selection of an inland terminal location. Similarly, Özmen and Aydoğan (2020) used the BWM in combination with the evaluation based on distance from average solution (EDAS) method to rank different LC locations in Kayseri, Turkey.

The literature focused on fuzzy applications is extensive. For example, Chen (2001) proposed a solution to the location problem under a fuzzy setting. Five criteria were taken into consideration: "*investment cost, expansion possibility, availability of acquirement material, human resources, and closeness to demand market*". Batanović, Petrović, and Petrović (2009) developed three new algorithms built on the search among possible location nodes. The authors applied comparison operations on discrete fuzzy sets to choose the best depot locations. Turskis and Zavadskas (2010) presented an Additive Ratio Assessment (ARAS) Fuzzy Method for the location selection problem. Erkayman et al. (2011) applied a Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (F-TOPSIS) approach in the eastern Asia Minor region of Turkey for LC location selection. Meanwhile, Kuo (2011) developed an F-DANP method for IDC location selection, considering six major seaports in Asia. Similarly, Karaşan and Kahraman (2019) proposed an F-DANP-TOPSIS model for freight village location selection for the city of Istanbul.

The methodology proposed by Li, Liu, and Chen (2011) considered two stages. The first was based on Axiomatic Fuzzy Sets (AFS) to evaluate the location of the LC. The final selection was carried out using TOPSIS. Another method was provided by Elevli (2014). The author applied a Fuzzy Preference Ranking Organization Method for Enrichment Evaluation (F-PROMETHEE) to the evaluation of five possible locations for the establishment of a LC in Samsun, Turkey. More recently, Ayadi et al. (2021) compared the location rankings provided by F-PROMETHEE and F-MAIRCA after applying the fuzzy full consistency method (F-FUCOM) to the weighting of the criteria identified for the location of a logistics platform with a sustainability perspective. The sustainability perspective was also adopted by Kumar and Anbanandam (2020). In contrast, the authors adopted an intuitionistic fuzzy integrated Analytic Hierarchy Process (IF-AHP) and TOPSIS approach to this end. Four Multimodal freight terminal (MFT) locations in India were evaluated.

Pham, Ma, and Yeo (2017) proposed an F-Delphi-TOPSIS approach from the logisticians' viewpoint in Vietnam. Fuzzy Analytic Hierarchy Process is combined with spatial statistics in the research provided by Önden et al. (2018). Yazdani, Chatterjee, Pamučar, and Chakraborty (2020) applied data envelopment analysis (DEA), full consistency (FUCOM) and combined compromise solution (CoCoSo) methods under a rough setting for the LC location selection in five Spanish autonomous communities. Recently, Agrebi and Abed (2021) developed a fuzzy multi-attribute, multi-actor decision making approach and applied it to a company interested in the selection of a new DC location. The contribution of Alidrisi (2021) is based on considering effectiveness and efficiency in the selection process. Kieu, Nguyen, Nguyen, and Ho (2021) focused on a model based on Spherical Fuzzy AHP and CoCoSo to support the distribution location selection problem of perishable agricultural products. Önden and Eldemir (2022) proposed an iterative solution approach based on fuzzy AHP and GIS's spatial and network analysis capabilities to determine the locations of logistics centers in metropolitan areas.

More recently, Puška et al. (2023) focused on the problem of selecting the location of DCs in a specific district in Bosnia and Herzegovina.

Table 1 presents a summary of the main contributions and research gaps covered by the current literature. As can be seen in the table, the methods analyzed do not consider a comparison of ANP and DANP, and are developed at company, city, or regional level. The applications have been predominantly developed within the Asian context, although some applications have also been provided in European regions. As far as current knowledge extends, this is the first paper to focus on the problem of locating distribution centers on a global level and, more specifically, on the location of an IDC with consideration of different European countries.

3. Methodology

The research methodology proposed in this section provides a structured and systematic framework for addressing the research questions and providing valuable insights into the problem of determining optimal locations for an IDC in Europe. More specifically, applied research methodology:

- Provides a thorough examination of research problems through the identification of criteria for IDC location selection and application of advanced MCDM approaches for location analysis.
- Ensures that the selected criteria are based on a combination of relevant literature review as well as on existing knowledge and practical insights from industry professionals.
- Involves an analysis of five of the most logistically intensive regions in Europe which enhances its relevance and applicability to real-world scenarios.
- Through the use of ANP and DEMATEL-ANP, provides a systematic evaluation of multiple criteria and their relationships leading to greater robustness in decision-making outcomes.

The research methodology was divided into two main steps. The first one consisted of the identification and selection of criteria for the location of IDCs (RQ1). A number of dimensions and criteria were identified based on relevant literature and expert opinions from the logistics sector. The dimensions were associated with different sets of criteria that best describe the IDC location problem. The second step involved a location analysis in five logistics-intensive regions of Europe to comply with RQ2. For this purpose, a MCDM approach based on ANP and DANP was developed, a performance analysis was carried out, and findings and conclusions were derived. The following sections describe the procedure in detail.

3.1. Identification and selection of criteria for the location of IDCs

The construction of the hierarchical structure and its evaluation was carried out in collaboration with a group of fifteen logistics experts. The experts were part of a network of collaborators in different projects in the supply chain field (e.g. Lead, Next-Net, Inspire): 1 manager of a LC management entity, 2 logistics managers of a user company, 3 managers of logistics operators, 1 full Professor of transportation, 3 researchers in logistics and supply chain management, 1 expert in multicriteria decision making and logistics, 3 experts in logistics infrastructure, 1 administration representative.

The participation of the experts in the research is described in more detail as follows: (1) A preliminary list of dimensions (D) and criteria (C) (10 and 66, see Table 2) was proposed by the research team (the Analyst Group – AG), as part of a project funded by the Regional Government of Aragon. The data collection process included the evaluation of relevant data sources from numerous databases of different organizations (World Bank, Eurostat, national statistical databases, international consultancy firms, port authorities, real estate companies, transport operators, etc.) as well as personal meetings with experts in the field of transport and logistics.

The dimensions, which are defined as follows, combined the AG's criteria with those of the IDC location:

- Regional system attractiveness: logistics incentives of a region as a result of previous investments in logistics competences that allow for a minimization of costs and a better integration in the logistics system.
- Demographics: related to the characteristics of the population of a specific region.
- Industry: linked to the peculiarities of the economic and productive activity of companies in a region.

Table 1
Summary of the main findings in the literature related to the DC location selection problem.

Reference	Problem	Method	Research gap covered	Main contributions
Agrebi and Abed (2021)	DC location	Fuzzy multi-attribute and multi-actor decision-making approach	Include qualitative criteria in the decision process.	The model restricts the field of study, and focus only on the selection between the best alternativesThis row stands out from the rest. Please unify and remove the gray background and the separator stripe. In addition, in the preview view, this reference is repeated
Alidrisi (2021)	DC location	PROMETHEE II and Data envelopment analysis	Develop a productivity evaluation model	The author considers effectiveness and efficiency in the selection process
Ayadi et al. (2021)	Logistics Platform selection in Republic of Tunisia	F-FUCOM; F-PROMETHEE; F-MAIRCA	Definition and development of fuzzy compensatory and partially compensatory composite indicators for locating a logistics platform from a sustainable perspective.	The paper studies the impact of limited and weak sustainability on the location problem. Economic and environmental criteria were found to be the most important for the location selection
Batanović et al. (2009)	Generic location for LCs in a distribution company	Fuzzy set theory	Comparison between alternatives consider demand at nodes are imprecise and uncertain.	Three network-covering problems are formulated. Decision under uncertain environment
Chen (2001)	Urban DC location in a company	Fuzzy set theory	Formulation of the location problem that mimics, as closely as possible, the reality of a broad class of facility location tasks.	Criteria selected by the company. Decision is made under fuzzy environment
Dupas et al. (2023)	Optimal location of urban consolidation centers (UCCs) in the city of Bordeaux (France)	Mixed-integer programming (MIP)	Generic evaluation method based on a MIP model to test scenarios implementing UCCs compared to the classical distribution scenario (i.e., without UCCs).	Determination of the best configuration of the distribution network with respect to certain design or use choices such as the capacity and the number of UCCs and the delivery modes.
Elevli (2014)	LC location in Turkey	F-PROMETHEE	The use of the chosen method (F-PROMETHEE) in the selection of a LC location.	Results show the use of PROMETHEE is suitable when site information is uncertain and there is subjectivity
Erkayman et al. (2011)	LC selection in Turkey	F-TOPSIS	The use of the chosen method (F-TOPSIS) in the selection of a LC location.	Decision is made under fuzzy environment. The model considers the vagueness of the subjective decision making
Essaadi et al. (2016)	Survey for hub location selection criteria	Literature review	Simultaneous assessment of the location at national and subnational level.	Structuration of criteria by geographical level and family. A specific list of criteria according to problem typology is not provided
Kampf et al. (2011)	Public LCs location in the Czech Republic	Weighted Sum Approach	First approach for the location of a public LC in the Czech Republic	A characterization of LC and DC in the Czech Republic is provided
Karaşan and Kahraman (2019)	Freight village location selection for the city of Istanbul, Turkey	DANP-Topsis	The use of the chosen method (DANP-Topsis) in the selection of a freight village location.	Validation of the efficiency of the method by the Simple Additive Weighting method
Kieu et al. (2021)	DC location	Spherical Fuzzy AHP and CoCoSo methods	Focus on perishable agricultural products	Incorporate uncertainty in the decision process.
Kumar and Anbanandam (2020)	Multimodal freight terminal location under social, technical, economic, environmental, and political (STEEP) sustainability. Application in India	IF-AHP and IF-TOPSIS	Identification of STEEP criteria for the location assessment. First study to propose technical and political sustainability dimensions.	Results revealed that technical sustainability is the most important criteria of Multimodal freight terminal location
Kuo (2011)	International DC location in six Pacific Asia ports	F-DEMATEL-AHP/ ANP	Handle the independent and dependent criteria that exist simultaneously in real-life situations.	The proposed method can overcome problems of the characteristic of criteria existing simultaneously as dependent and independent
Li et al. (2011)	LC location in cities	AFS-TOPSIS	An integration of different methodologies to a comprehensive location decision.	The model considers town planning and logistics
Li and Zhou (2021)	Location of cold chain logistics DC	A non-dominated sorting genetic algorithm II (NSGA-II)	A multi-objective location model of cold chain logistics distribution center considering carbon emission	Determining the location of cold chain logistics DC by considering three objectives: minimum logistics cost, minimum carbon emission, and maximum customer satisfaction
Liang et al. (2021)	Inland terminal location selection of the Maersk shipping line	BWM	The inland terminal location selection problem from the scope of a shipping line.	Four layers are considered: transport, logistics, infrastructure, location. An efficient inland transport chain benefits all the involved stakeholders
Meidutė and Raudeliūnienė (2011)	Assessment of internal and external factors of competition for LCs establishment	Complex multiple criteria assessment	Assessment of internal and external factors of competition of logistics centers.	Identification, assessment, and estimation of external and internal factors of LC location
Önden et al. (2018)	Suitability degrees of 19 locations in the framework of a LC project	F-AHP, spatial statistics and analysis approaches	Approach developed in the framework of a strategic development plan. Evaluation of public LC locations.	Spatial suitability is analyzed. The method detect changes in the decision environment.
Önden and Eldemir (2022)	Location of logistics center in metropolitan areas	Fuzzy AHP and GIS-based spatial and network analysis	Holistic approach that integrates different methods for addressing logistics center problems	A multiple facility location decision for logistics centers in a metropolitan area is studied with a comprehensive perspective

(continued on next page)

Table 1 (*continued*)

Reference	Problem	Method	Research gap covered	Main contributions
Agrebi and Abed (2021)	DC location	Fuzzy multi-attribute and multi-actor decision-making approach	Include qualitative criteria in the decision process.	The model restricts the field of study, and focus only on the selection between the best alternativesThis row stands out from the rest. Please unify and remove the gray background and the separator stripe. In addition, in the preview view, this reference is repeated
Özmen and Aydoğan (2020)	LC location in Kayseri, Turkey	BMW-EDAS	Application for a specific area in Turkey, proposing administrative inference.	Methodology applied for the first time in LC location literature.
Pamučar, Tarle, and Parezanovic (2018)	Multimodal LC selection in eight locations by the Danube River	DEMATEL -MAIRCA	First approach considering DEMATEL and MAIRCA for the location selection problem.	Hybrid application considering MAIRCA, a recently developed MCDM methodology
Peker et al. (2016)	LC site selection in Trabzon, Turkey	ANP-BOCR	First approach considering ANP/BOCR method for the location selection problem.	The model considers the interdependency relationships among the factors
Pham et al. (2017)	LC location in Vietnam	F-Delphi-Topsis	Benchmarking framework for the location selection problem based on the logisticians' perspective.	The perspective of logisticians under an environment of uncertain information is adopted
Puška et al. (2023)	DC selection in a specific district in Bosnia and Herzegovina	Fuzzy set theory	Evaluation of a potential DC location in BiH's Brcko District	The model combines fuzzy sets along with the IMF SWARA and fuzzy CRADIS methods.
Strutynska et al. (2018)	Optimization for regional DCs location. Application to four cities in Central Ukraine	Theory of scheduling and optimization	The optimization model considers the transportation networks and availability of infrastructure in the vicinity of the possible arrangement.	The model combines geographic and social factors. A desirability function is proposed
Taouktsis and Zikopoulos (2024)	Location of DC with minimal aid distribution distance in a humanitarian logistics network	A hybrid approach based on Deep Neural Network (DNN) and Farthest Insertion (FI) algorithm	New hybrid approach to apply in real-world humanitarian logistics network scenarios to develop a robust distribution infrastructure	An innovative approach with the perspective of improving the effectiveness and efficiency of humanitarian logistics decision-making processes
Turskis and Zavadskas (2010)	LC location	ARAS-F	First approach considering ARAS-F for the location selection problem.	The utility function value is directly proportional to the relative effect of weights of the considered criteria
Yazdani et al. (2020)	LC location in the Spanish autonomous communities	R-DEA, R-FUCOM, R-CoCoSo	First integrated evaluation approach for logistics center selection.	A ranking of the most suitable communities is provided. The model can be used for the formulation of warehousing and transportation strategies
Zhang and Yin (2017)	LC location	MATLAB genetic algorithm toolbox	First approach using a genetic algorithm for the location selection problem.	The algorithm solves the problem to minimize total transportation costs
Zhang et al. (2021)	Location of a cold chain distribution center in Wuhan (China)	Bi-level linear programming and cloud particle swarm optimization	Determining the location of low-carbon competitive distribution centers by combining low-carbon and competitive location	A scientific basis regarding decisions concerning the location of new cold chain distribution centers by the government, and ideas for energy conservation improvement and carbon emissions reduction by the whole society.
Zhen et al. (2019)	Location of (re)manufacturers and LCs in China	Stochastic Mixed integer non-linear programming model, and an improved tabu search heuristic algorithm	First approach jointly considering the location and scale of facilities.	The scale of the facilities is included on the decision model. Inspection should be performed at producer locations

- Infrastructure: referring to the basic structures and resources available in a region that support the functionality of firms and households.
- Logistics information: provides information to manage goods and track delivery throughout the supply chain.
- Workforce: associated with the characteristics of the people available in a region to support business activity.
- Transport costs: the monetary value associated with the different means of transport.
- Global shipments: related to the characteristics of the processes associated with the global shipment of goods.
- Taxes: the monetary imposition that governments set on the global shipping of goods.
- Sustainability: regulation and impact of transport activity in a region.

(2) The set of dimensions and criteria identified were distributed in a questionnaire to the experts to corroborate their importance for inclusion in the model. Each expert evaluated the importance of the dimensions and criteria on a scale ranging from 0 (very unimportant), 3 (important), 5 (fair), 7 (important) to 10 (very important) (Chen, Hsu, & Tzeng, 2011). There were allowed intermediate values (1, 2, 4, 6, 8, 9) representing intermediate preferences between the scales considered. As an additional outcome of this phase of the analysis, other criteria proposed by the experts, which were not initially considered by the AG, were obtained.

(3) The AG obtained the preferred subset of dimensions/ criteria using Triangular Fuzzy Numbers (TFN) from the experts' answers. A TFN is a triplet (a,b,c), where a (smallest likely value) and c (largest likely value) membership functions are 0, and b (most probable value) membership function is 1 (Pamučar et al., 2012). In the analysis, the minimum threshold was 7.5 (a = 6.5, b = 7 (important in the scale), c = 7.5) (Chen et al., 2011). The preferred list of dimensions and criteria according to the expert's opinion (those with a mean of 7.5 and above) is shown in Table 3. A total of 7 dimensions and 25 criteria were selected. The relationships between the 7 dimensions are depicted in Fig. 1.

(4) The selected dimensions and criteria were used as the basis for developing the model. A second questionnaire was developed for the

Table 2
Dimensions and criteria for IDC location.

Dimension	Criteria	Source
Regional logistics system attractiveness	Ease of access to seaport	Agrebi & Abed, 2021; Ayadi et al., 2021; Yazdani et al., 2020
	Ease of access to airport	Agrebi & Abed, 2021; Ayadi et al., 2021; Yazdani et al., 2020; Puška et al. (2023)
	Closeness to industrial hubs	Agrebi & Abed, 2021; Ayadi et al., 2021; Erkayman et al., 2011; Kumar & Anbanandam, 2020; Özmen & Aydoğan, 2020; Pham et al., 2017; Yazdani et al., 2020; Kieu et al. (2021)
	Closeness to logistics hubs	Agrebi & Abed, 2021; Erkayman et al., 2011; Kumar & Anbanandam, 2020; Yazdani et al., 2020; Kieu et al. (2021)
	Logistics potential of the region (industrial demand for logistics services/indirect businesses)	*Authors contribution*
	Intensity of transport flows in relation to different modes of transport (traffic congestion)	Karaşan & Kahraman, 2019; Kumar & Anbanandam, 2020; Li et al., 2011; Özmen & Aydoğan, 2020; Peker et al., 2016
Demographics	Population density	Kampf et al., 2011; Önden et al., 2018; Strutynska et al., 2018
	Resident buying power per capita	Kampf et al., 2011
	Residents' average age	Authors contribution
	Active population	Authors contribution
Industry	Level of political stability in the region	Kumar & Anbanandam, 2020; Özmen & Aydoğan, 2020;
	Level of industry diversity	Elevli, 2014
	Import to export ratio	*Authors contribution*
	Ratio of inbound to outbound freight volumes	*Authors contribution*
	Number of carriers in the region	*Authors contribution*
	Number of retailers in the region	*Authors contribution*
Infrastructure	Availability of highways within the region	Essaadi et al., 2016; Kampf et al., 2011; Karaşan & Kahraman, 2019; Strutynska et al., 2018
	Connectivity of highways to logistics hubs	Agrebi & Abed, 2021; Ayadi et al., 2021; Elevli, 2014; Önden et al., 2018; Pham et al., 2017; Yazdani et al., 2020; Puška et al. (2023)
	Quality of highways	Essaadi et al., 2016; Karaşan & Kahraman, 2019; Özmen & Aydoğan, 2020;
	Availability of seaports within the region	Ayadi et al., 2021; Elevli, 2014; Essaadi et al., 2016; Kampf et al., 2011; Karaşan & Kahraman, 2019; Önden et al., 2018; Özmen & Aydoğan, 2020; Pham et al., 2017; Strutynska et al., 2018
	Capacity of the seaport	Karaşan & Kahraman, 2019
	Quality of seaport services	Essaadi et al., 2016; Karaşan & Kahraman, 2019; Önden et al., 2018; Özmen & Aydoğan, 2020;
	Availability of airports within region	Ayadi et al., 2021; Elevli, 2014; Essaadi et al., 2016; Kampf et al., 2011; Karaşan & Kahraman, 2019; Önden et al., 2018; Özmen & Aydoğan, 2020; Pham et al., 2017; Strutynska et al., 2018
	Capacity of the airport	Karaşan & Kahraman, 2019
	Quality of airport services	Agrebi & Abed, 2021; Essaadi et al., 2016; Karaşan & Kahraman, 2019; Yazdani et al., 2020
	Availability of railroads within region	Ayadi et al., 2021; Elevli, 2014; Essaadi et al., 2016; Kampf et al., 2011; Kumar & Anbanandam, 2020; Karaşan & Kahraman, 2019; Önden et al., 2018; Özmen & Aydoğan, 2020; Pham et al., 2017; Strutynska et al., 2018
	Capacity of railroads for freight transportation	Karaşan & Kahraman, 2019
	Quality of railroad services	Agrebi & Abed, 2021; Essaadi et al., 2016; Karaşan & Kahraman, 2019; Özmen & Aydoğan, 2020; Yazdani et al., 2020
	Level of intermodal transportation	Karaşan & Kahraman, 2019; Kumar & Anbanandam, 2020; Özmen & Aydoğan, 2020;
	Cost of land acquisition (square meter)	Agrebi & Abed, 2021; Ayadi et al., 2021; Elevli, 2014; Kumar & Anbanandam, 2020; Li et al., 2011; Özmen & Aydoğan, 2020; Peker et al., 2016; Pham et al., 2017; Turskis & Zavadskas, 2010; Yazdani et al., 2020; Kieu et al. (2021); Puška et al. (2023)
	Cost of Rent	*Authors contribution*
	Availability of land	Essaadi et al., 2016; Özmen & Aydoğan, 2020;
	Availability of pre-built facilities	*Authors contribution*
	Land purchasing cost	Agrebi & Abed, 2021; Ayadi et al., 2021; Elevli, 2014; Kumar & Anbanandam, 2020; Li et al., 2011; Özmen & Aydoğan, 2020; Peker et al., 2016; Pham et al., 2017; Turskis & Zavadskas, 2010; Yazdani et al., 2020; Puška et al. (2023)
	Structure and ownership of land	Elevli, 2014; Özmen & Aydoğan, 2020; Peker et al., 2016
	Possibility of expansion	Agrebi & Abed, 2021; Ayadi et al., 2021; Chen, 2001; Elevli, 2014; Karaşan & Kahraman, 2019; Kumar & Anbanandam, 2020; Liang et al., 2021; Özmen & Aydoğan, 2020; Peker et al., 2016; Pham et al., 2017; Turskis & Zavadskas, 2010; Yazdani et al., 2020; Puška et al. (2023)
	Security in the area	Agrebi & Abed, 2021; Ayadi et al., 2021; Kumar & Anbanandam, 2020; Özmen & Aydoğan, 2020; Yazdani et al., 2020; Puška et al. (2023)
	Earthquake risk	Karaşan & Kahraman, 2019
Logistics information	Ease of tracking shipments	*Authors contribution*
	Quality of logistics information systems used	Özmen & Aydoğan, 2020
	Workforce	

(*continued on next page*)

Table 2 (*continued*)

Dimension	Criteria	Source
	Proximity to customers	Agrebi & Abed, 2021; Chen, 2001; Liang et al., 2021; Pham et al., 2017; Yazdani et al., 2020; Puška et al. (2023)
Workforce	Level of skilled labor	Essaadi et al., 2016
	Availability of logistics educational programs	*Authors contribution*
	Labor regulations	*Authors contribution*
	Labor availability	Chen, 2001; Elevli, 2014; Kumar & Anbanandam, 2020
	Labor costs (€/month)	Ayadi et al., 2021; Karaşan & Kahraman, 2019; Kumar & Anbanandam, 2020; Özmen & Aydoğan, 2020; Pham et al., 2017
	Level of conflicts	*Authors contribution*
	Schedule flexibility	*Authors contribution*
	Turnover rate	*Authors contribution*
Transport costs	Medium/ long distance	Ayadi et al., 2021; Karaşan & Kahraman, 2019; Kumar & Anbanandam, 2020; Liang et al., 2021; Özmen & Aydoğan, 2020; Peker et al., 2016; Pham et al., 2017
	Last mile	Ayadi et al., 2021; Karaşan & Kahraman, 2019; Kumar & Anbanandam, 2020; Liang et al., 2021; Özmen & Aydoğan, 2020; Peker et al., 2016; Pham et al., 2017
	Main haulage costs (per container)	*Authors contribution*
	Airplane (per kg)	Ayadi et al., 2021; Karaşan & Kahraman, 2019; Kumar & Anbanandam, 2020; Özmen & Aydoğan, 2020; Peker et al., 2016; Pham et al., 2017
	Railway	Ayadi et al., 2021; Karaşan & Kahraman, 2019; Kumar & Anbanandam, 2020; Özmen & Aydoğan, 2020; Peker et al., 2016; Pham et al., 2017
Global shipments	Level of documentation	*Authors contribution*
	Ease of customs clearing	*Authors contribution*
	Ease of loading/unloading	*Authors contribution*
	Level of supply chain fluidity	*Authors contribution*
Taxes	Tax rate	Agrebi & Abed, 2021; Ayadi et al., 2021; Karaşan & Kahraman, 2019; Kumar & Anbanandam, 2020; Yazdani et al., 2020
	Possibility of VAT deferment	Authors contribution
	Fees at ports	Agrebi & Abed, 2021; Ayadi et al., 2021; Karaşan & Kahraman, 2019; Kumar & Anbanandam, 2020; Özmen & Aydoğan, 2020; Yazdani et al., 2020
	Fees at customs	*Authors contribution*
Sustainability	Ratio of green companies	*Authors contribution*
	Ratio of green logistics service providers	*Authors contribution*
	Level of regional environmental regulations	*Authors contribution*
	Environmental impact of transportation activities	Agrebi & Abed, 2021; Karaşan & Kahraman, 2019; Peker et al., 2016; Pham et al., 2017; Yazdani et al., 2020

Table 3
Dimensions and criteria selected for the location of an IDC.

Dimension (D)	Criteria (C)
Regional logistics system attractiveness (D1)	• Ease of access to seaport (C1) • Closeness to logistics hubs (C2) • Logistics potential of the region (industrial demand for logistics services/indirect businesses) (C3) • Intensity of transport flows in relation to different modes of transport (traffic congestion) C4)
Industry (D2)	• Level of industry diversity (C5) • Number of carriers in the region (C6) • Number of retailers in the region (C7)
Infrastructure (D3)	• Availability of highways within the region (C8) • Connectivity of highways to logistics hubs (C9) • Quality of highways (C10) • Capacity of railroads for freight transportation (C11) • Quality of railroad services (C12) • Level of intermodal transportation (C13) • Cost of land acquisition (square meter) (C14)
Workforce (D4)	• Level of skilled labor (C15) • Availability of logistics educational programs (C16) • Labor regulations (C17) • Labor availability (C18) • Labor costs (€/month) (C19)
Transport costs (D5)	• Last mile (C20) • Main haulage costs (per container) (C21)
Global shipments (D6)	• Ease of loading/unloading (C22) • Level of supply chain fluidity (C23)
Taxes (D7)	• Tax rate (C24) • Possibility of VAT deferment (C25)

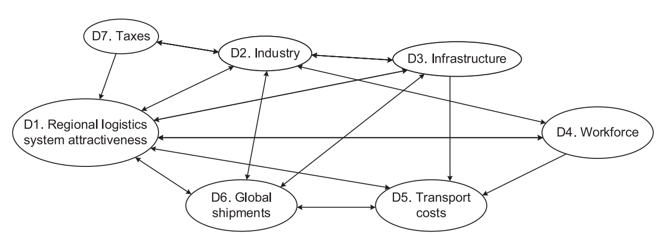

Fig. 1. Relationship between the dimensions identified as defined by the experts.

application of ANP and DANP. The dimensions and criteria were structured into matrices. In ANP, the experts were asked to compare with respect to the clustering which of the criteria in each of the rows concerning each of the criteria in each of the columns was more important, and to assess the influence of the chosen criterion using the scale of Saaty (all the elements on the diagonal have the same importance). For example, in Table 4, the experts were asked to identify whether C5 or C6 is the most important for the industry and to weigh that importance.

Table 4
Example of matrices to be filled in by the experts.

Industry (D2)	Level of industry diversity (C5)	Number of carriers in the region (C6)	Number of retailers in the region (C7)
Level of industry diversity (C5)	Filled by the experts	Filled by the experts	Filled by the experts
Number of carriers in the region (C6)	Filled by the experts	Filled by the experts	Filled by the experts
Number of retailers in the region (C7)	Filled by the experts	Filled by the experts	Filled by the experts

For the application of DANP, the experts were asked to evaluate the interdependency between criteria. For this, they gave their opinion about the impact one criterion has on another using a scale from 0 to 4 (all the elements on the diagonal have no impact). For example, in Table 4, we asked experts to identify whether C5 has an impact on C6 and to weigh this impact.

A total of 5 responses were obtained from the same group of experts in the period between June and September 2022. Responses were obtained through a personal interview and completed surveys from 1 university professor, 2 researchers from eminent research institutes and 2 representatives of logistics-service providers.

The network structure for the selection of the preferred IDC location is illustrated in Fig. 2. At the level of dimensions and criteria, the interrelationships within and between dimensions/criteria (dotted lines) were considered.

3.2. ANP and DANP methods

The ANP introduced by Tomas Saaty (Saaty, 1996) presents a framework that treats dependence within a cluster (inner dependence) and between different clusters (outer dependence). The problem can be structured as the coupling of two parts (Saaty, 2013). The first part includes a control hierarchy or a network of criteria and sub-criteria in the system under study, where the goal can be included. The second part identifies the network of influences between elements and groupings. This stands in contrast to the Analytic Hierarchy Process (AHP) which is characterized by its hierarchical and linear structure wherein the goal resides at the top and the alternatives are positioned at the lower levels (Saaty & Vargas, 2006). The ANP has emerged in the literature as the preferred multicriteria analysis method for modeling dependence and feedback. More than a thousand papers since 2005 in the SCOPUS database have applied this methodology (Golcuk & Baykasoglu, 2016).

Decision networks within ANP consist of clusters, their elements, and the links between elements (Büyüközkan & Güleryüz, 2016). The links between elements within the same cluster indicate the inner dependencies of the elements, while the links between a parent element in one cluster and its dependent elements in another cluster represent the outer dependencies. Outer dependencies between two clusters in both directions are known as feedback (Karpak & Topcu, 2010). However, the treatment of interdependencies in the ANP method is not objectively addressed in relation to the considered decision-making problem. For that reason, the DEMATEL method is used in combination with ANP. In

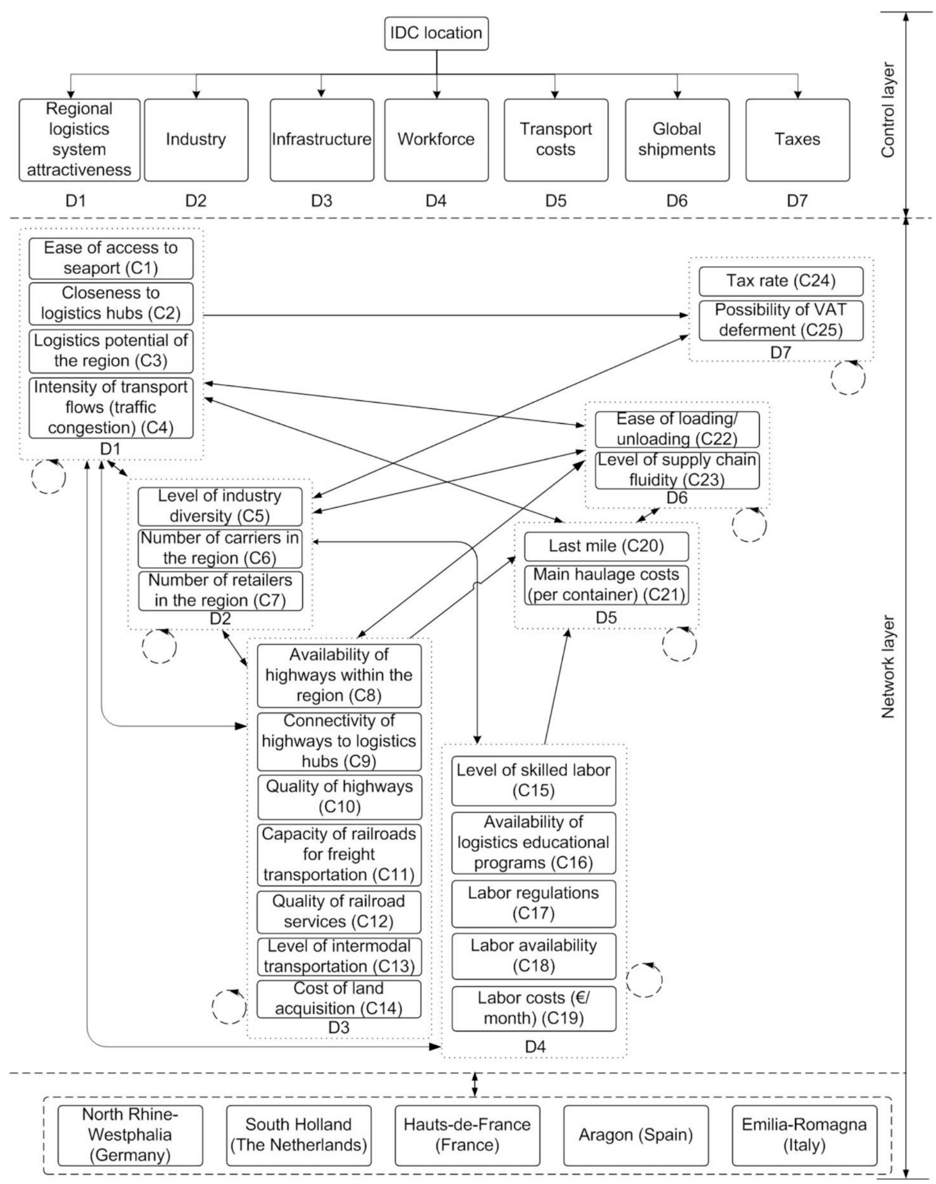

Fig. 2. Network structure of the evaluation model.

contrast to ANP, DANP modifies the pairwise comparisons and forms a comprehensive unweighted matrix in which the pairwise comparisons are not performed only within clusters, but also for the whole system according to the structure of the problem (Milenković et al., 2021). Then, the total relation matrices among the clusters are used to weigh the appropriate parts of the supermatrix to get the weighted supermatrix. The weighted supermatrix is then raised to limiting powers to obtain the final priorities (Golcuk & Baykasoglu, 2016).

The strategy of this paper is to apply the ANP approach for the selection of an IDC location and then combine DEMATEL with ANP to improve the assessment of interdependencies at the dimension and criteria level. The steps of both approaches are illustrated in Fig. 3.

The following set of steps (Milenković et al., 2021) describes the DANP approach for the selection of an IDC location:

Step 1. Conduct a literature survey and interviews with experts directly and indirectly involved in transportation, logistics and supply chain-related activities.

Step 2. Design the questionnaire based on the experience, the literature survey and the expert's knowledge.

Step 3. Collect expert opinions on the dimensions and attributes and select the preferred subset based on TFNs.

Step 4. Apply the DEMATEL methodology to determine the interdependence between dimensions and attributes (Step 4.1–4.5):

Step 4.1. Calculate the average direct relation matrix (DRM).

Calculate the average direct relation matrix A. Experts use a scale from 0 to 4 (no influence (0), low influence (1), medium influence (2), high influence (3) and very high influence (4)), to compare dimensions and attributes pairwise in terms of influence and direction. From these entries, a matrix A of *nxn* dimensions, known as the average DRM, is constructed (1). Each element a_{ij} of matrix A represents the impact of dimension/attribute *i* on dimension/attribute *j* and is calculated as the average of all experts' inputs for a given *ij* pair of dimensions or attributes.

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1j} & \cdots & a_{1n} \\ \vdots & & \vdots & & \vdots \\ a_{i1} & & a_{ij} & & a_{in} \\ \vdots & & \vdots & & \vdots \\ a_{n1} & & a_{nj} & & a_{nn} \end{bmatrix} \tag{1}$$

Step 4.2. Normalize the DRM. The normalized DRM (NDRM) represents a multiplication of the matrix *A* and *k*:

$$N = A\ x\ k \tag{2}$$

where

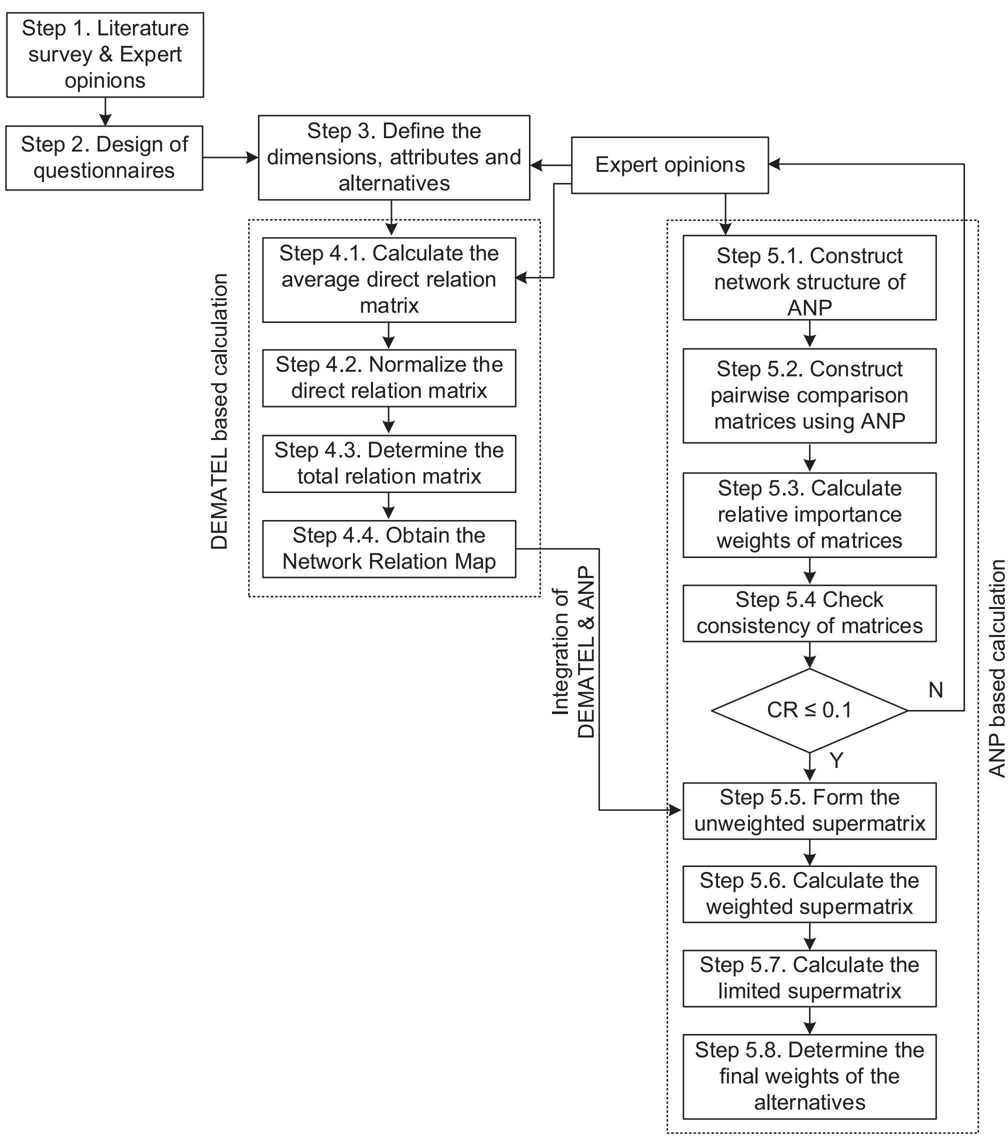

Fig. 3. Evaluation framework: A general overview.

$$k = min\left[\frac{1}{max_i \sum_{j=1}^{n} |a_{ij}|}, \frac{1}{max_j \sum_{j=1}^{n} |a_{ij}|}\right] \quad (3)$$

Step 4.3. Determine the total-influence matrix.

The total influence matrix $T = [t_{ij}]_{nxn}$ is obtained from matrix N. Transition theory is applied and the direct initial influence and the indirect influence of all components of the system are summed, therefore, the total influence is the sum of an infinite series (Lee, Tzeng, Yeih, Wang, & Yang, 2013).

$$T = N + N^2 + N^3 + \cdots + N^m = N(I-N)^{-1}, \text{when } m \rightarrow \infty \quad (4)$$

where I is an $n \times n$ identity matrix.

Step 4.4. Obtain the Inter-Relationship Map.

The Inter-Relationship Map (IRM) represents a diagram illustrating the roles that dimensions and attributes have in the evaluation of the alternative location of the IDC with the horizontal axis ($r + c$) and the vertical axis (r-c) (Dalvi-Esfahani, Niknafs, Kuss, Nilaski, & Afrough, 2019). The sum ($r_i + c_j$), known as "prominence", represents the importance that dimension/attribute i plays in the considered decision-making problem, while the difference (r_i - c_j), known as "relation", shows the net effect that dimension/attribute i contributes to the evaluation of the IDC location alternative. A positive result of (r_i - c_j), means that the factor i is a net causer, while a negative result (r_i - c_j) means that the factor i is a net receiver. To obtain a suitable diagram, it is necessary to establish the threshold value of the level of influence. This threshold reduces the complexity of the structural relation model implied by the matrix T (Lee et al., 2013). Independent factors, i.e., those that have low prominence and relationship and are relatively unconnected to the system can be identified as those that meet r-$c < 0$ and $r + c <$ mean (Si, You, Liu, & Zhang, 2018).

To draw the IRM it is necessary to calculate the sums of the rows r and columns c of the total relation matrix T:

$$r = (r_i)_{n\times 1} = \left[\sum_{j=1}^{n} t_{ij}\right]_{n\times 1} \quad (5)$$

$$c = (c_j)_{n\times 1} = (c_j)'_{1\times n} = \left[\sum_{i=1}^{n} t_{ij}\right]'_{1\times n} \quad (6)$$

where r_i: represents the total effect, both direct and indirect, that dimension/attribute i has on the other dimensions/attributes; c_j: represents the sum of the j^{th} column, in matrix T represents the total effects both direct and indirect, that dimension/attribute j has received from other dimensions/attributes j. The superscript ´ denotes transpose.

The influence matrix T can be divided into T_D based on dimensions and T_A based on attributes.

$$T_a = \begin{array}{c} \\ \\ D_1 \begin{matrix} a_{11} \\ \vdots \\ a_{1m_1} \end{matrix} \\ D_i \begin{matrix} a_{i1} \\ \vdots \\ a_{im_i} \end{matrix} \\ D_n \begin{matrix} a_{n1} \\ \vdots \\ a_{nm_n} \end{matrix} \end{array} \begin{array}{c} \begin{matrix} D_1 & \cdots & D_i & \cdots & D_n \\ a_{11}..,a_{1m1} & \cdots & a_{i1}...a_{im_i} & \cdots & a_{m_1}...a_{nm_n} \end{matrix} \\ \begin{bmatrix} T_a^{11} & \cdots & T_a^{1j} & \cdots & T_a^{1n} \\ \vdots & & \vdots & & \vdots \\ T_a^{i1} & \cdots & T_a^{ij} & \cdots & T_a^{in} \\ \vdots & & \vdots & \ddots & \vdots \\ T_a^{n1} & \cdots & T_a^{nj} & \cdots & T_a^{nn} \end{bmatrix} \end{array} \quad (7)$$

Matrix T_a^{11} represents a matrix of attributes owned by group D_1 as well as the influences with respect to the attributes from dimension D_1 (8). T_a^{12} is a matrix of attributes related to D_2 and the influences with respect to the attributes from dimension D_2. The rest of the elements of the T_a matrix can be described similarly.

$$T_a^{11} = \begin{bmatrix} t_{a^{11}}^{11} & \cdots & t_{a^{1j}}^{11} & \cdots & t_{a^{1m_1}}^{11} \\ \vdots & & \vdots & & \vdots \\ t_{a^{i1}}^{11} & \cdots & t_{a^{ij}}^{11} & \cdots & t_{a^{im_1}}^{11} \\ \vdots & & \vdots & \ddots & \vdots \\ t_{a^{m11}}^{11} & \cdots & t_{a^{m1j}}^{11} & \cdots & t_{a^{m1m1}}^{11} \end{bmatrix} \quad (8)$$

Steps 5.1–5.8 (Fig. 3) contain the ANP methodology for calculating the relative weights of nodes in the network (Büyüközkan & Güleryüz, 2016).

Step 5.1. Construction of the problem network.

Step 5.2. Determination of the relative weights of the dimensions/attributes and construction of pairwise comparison matrix using the scale of Saaty.

Step 5.3. Calculate the eigenvalues and eigenvectors of the comparison matrices. In case there are N attributes or criteria $(C_1, \ldots, C_j, \ldots, C_n)$ and the pairwise comparison matrix $A = a_{ij}$, where a_{ij} represents the relative importance of criteria C_i and C_j. For all i and j it is necessary that $a_{ij} = 1$ and $a_{ij} = 1/a_{ji}$. The row vector average method is used for the normalization of the results. The approximate weight W_i is calculated as follows:

$$W_i = \frac{\sum_{j=1}^{n}\left(\frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}\right)}{n} \forall i, j = 1, 2 \ldots, n \quad (9)$$

The largest eigenvalue λ_{max} is obtained from the formula:

$$AW = \lambda W \lambda_{\max} = \frac{1}{n}\sum_{i=1}^{n}\frac{(AW)_i}{W_i} \quad (10)$$

Step 5.4. Consistency test. The consistency of the pairwise comparison is evaluated using the consistency index (CI) and the consistency ratio (CR):

$$CI = \frac{\lambda_{\max} - n}{n-1} \quad (11)$$

$$CR = \frac{CI}{RI} \quad (12)$$

If the CR is >0.1, the pairwise comparisons must be repeated. RI represents the random index. Experts can work under consensus or individually. In the case of individual judgments, it is necessary to synthesize all responses (Aguarón, Escobar, Moreno-Jiménez, & Turón, 2019).

The remaining steps represent the essence of the DANP approach.

Step 5.5. Determination of the unweighted supermatrix. The supermatrix in general form takes the following appearance (Supeekit, Somboonwivat, & Kritchanchai, 2016):

$$W = \begin{array}{c} \\ \\ D_1 \begin{matrix} a_{11} \\ \vdots \\ a_{1m_1} \end{matrix} \\ D_i \begin{matrix} a_{i1} \\ \vdots \\ a_{im_i} \end{matrix} \\ D_n \begin{matrix} a_{n1} \\ \vdots \\ a_{nm_n} \end{matrix} \end{array} \begin{array}{c} \begin{matrix} D_1 & \cdots & D_i & \cdots & D_n \\ a_{11}..,a_{1m1} & \cdots & a_{i1}...a_{im_i} & \cdots & a_{m_1}...a_{nm_n} \end{matrix} \\ \begin{bmatrix} W^{11} & \cdots & W^{1j} & \cdots & W^{1n} \\ \vdots & & \vdots & & \vdots \\ W^{i1} & \cdots & W^{ij} & \cdots & W^{in} \\ \vdots & & \vdots & \ddots & \vdots \\ W^{n1} & \cdots & W^{nj} & \cdots & W^{nn} \end{bmatrix} \end{array} \quad (13)$$

where D_n denotes the n^{th} dimension (cluster), a_{nm} refers to the n^{th} attribute in m^{th} dimension and W_{ij} is the principal eigenvector of the impact of the attributes owned by the j^{th} dimension compared to the i^{th} dimension (cluster). In case the j^{th} dimension has no influence, then $W_{ij} = [0]$.

To obtain the unweighted supermatrix, the total influence matrix T_a

must first be normalized. The normalized total influence matrix T_a^α has the following form:

$$T_a^\alpha = \begin{array}{c} \\ D_1 \begin{array}{c} a_{11} \\ \vdots \\ a_{1m_1} \end{array} \\ \vdots \\ D_i \begin{array}{c} a_{i1} \\ \vdots \\ a_{im_i} \end{array} \\ \vdots \\ D_n \begin{array}{c} a_{n1} \\ \vdots \\ a_{nm_n} \end{array} \end{array} \overset{\begin{array}{ccccc} D_1 & \cdots & D_i & \cdots & D_n \\ a_{11}\ldots a_{1m1} & \cdots & a_{i1}\ldots a_{im_i} & \cdots & a_{n1}\ldots a_{nm_n} \end{array}}{\begin{bmatrix} T_a^{\alpha_{11}} & \cdots & T_a^{\alpha_{1j}} & \cdots & T_a^{\alpha_{1n}} \\ \vdots & & \vdots & & \vdots \\ T_a^{\alpha_{i1}} & \cdots & T_a^{\alpha_{ij}} & \cdots & T_a^{\alpha_{in}} \\ \vdots & & \vdots & \ddots & \vdots \\ T_a^{\alpha_{n1}} & \cdots & T_a^{\alpha_{nj}} & \cdots & T_a^{\alpha_{nn}} \end{bmatrix}} \tag{14}$$

where $T_a^{\alpha 11}$ represents a normalized sum of the influences of factors a_{11}, …, a_{1m1} related to the attributes belonging to dimension D_1 and calculated as follows:

$$T_a^{\alpha_{11}} = \begin{bmatrix} t_{a^{11}}^{11}/d_1^{11} & \cdots & t_{a^{1j}}^{11}/d_1^{11} & \cdots & t_{a^{1m_1}}^{11}/d_1^{11} \\ \vdots & & \vdots & & \vdots \\ t_{a^{i1}}^{11}/d_i^{11} & \cdots & t_{a^{ij}}^{11}/d_i^{11} & \cdots & t_{a^{im_1}}^{11}/d_i^{11} \\ \vdots & & \vdots & \ddots & \vdots \\ t_{a^{m11}}^{11}/d_i^{11} & \cdots & t_{a^{m1j}}^{11}/d_i^{11} & \cdots & t_{a^{m1m1}}^{11}/d_i^{11} \end{bmatrix} = \begin{bmatrix} t_{a^{11}}^{\alpha 11} & \cdots & t_{a^{1j}}^{\alpha 11} & \cdots & t_{a^{1m_1}}^{\alpha 11} \\ \vdots & & \vdots & & \vdots \\ t_{a^{i1}}^{\alpha 11} & \cdots & t_{a^{ij}}^{\alpha 11} & \cdots & t_{a^{im_1}}^{\alpha 11} \\ \vdots & & \vdots & \ddots & \vdots \\ t_{a^{m11}}^{\alpha 11} & \cdots & t_{a^{m1j}}^{\alpha 11} & \cdots & t_{a^{m1m1}}^{\alpha 11} \end{bmatrix} \tag{15}$$

where d_i^{11} represents the sum of the influences of factors a_{11}, …, a_{1m1} associated with the first dimension (D_1):

$$d_i^{11} = \sum_{j=1}^{m_1} t_{a^{ij}}^{11}, \text{for } i = 1, 2, \ldots, m_1 \tag{16}$$

The elements $t_{a_{11}}^{11}$ represent the values of the attribute impacts a_{11}, …, a_{1m1} regarding the attributes pertaining to the dimension D_1, while the elements $t_{a^{11}}^{\alpha 11}$ are their normalized values.

The unweighted matrix W (13) is composed of the normalized values of the attribute influences $T_c^{\alpha_{nn}}$ which are calculated following the procedure explained above. The component matrices within the supermatrix W represent the values of the attribute influences among the different dimensions. For example, matrix W_{11} represents the values of the attribute impacts from dimension D_1 in relation to the attributes from dimension D_1 according to (17).

$$W^{11} = \begin{array}{c} c_{11} \\ \vdots \\ c_{1i} \\ \vdots \\ c_{1m1} \end{array} \begin{bmatrix} t_{a^{11}}^{\alpha 11} & \cdots & t_{a^{j1}}^{\alpha 11} & \cdots & t_{a^{m_1 1}}^{\alpha 11} \\ \vdots & & \vdots & & \vdots \\ t_{a^{1i}}^{\alpha 11} & \cdots & t_{a^{ji}}^{\alpha 11} & \cdots & t_{a^{m_1 i}}^{\alpha 11} \\ \vdots & & \vdots & \ddots & \vdots \\ t_{a^{1m1}}^{\alpha 11} & \cdots & t_{a^{jm1}}^{\alpha 11} & \cdots & t_{a^{m1m1}}^{\alpha 11} \end{bmatrix}^{c_{11} \cdots c_{1j} \cdots c_{1m1}} \tag{17}$$

Step 5.6. Calculation of the weighted supermatrix. The weighted supermatrix W_W is obtained by the same procedure, employing the normalized total influence matrix T_D and the unweighted supermatrix.

$$T_D = \begin{bmatrix} t_D^{11} & \cdots & t_D^{1j} & \cdots & t_D^{1n} \\ \vdots & & \vdots & & \vdots \\ t_D^{i1} & & t_D^{ij} & & t_D^{in} \\ \vdots & & \vdots & & \vdots \\ t_D^{n1} & \cdots & t_D^{nj} & \cdots & t_D^{nn} \end{bmatrix} \tag{18}$$

where t_D^{ij} represents the sum of influences of the T_a^{ij} matrix. The normalization is performed as follows.

$$T_D^\alpha = \begin{bmatrix} t_D^{11}/d_1 & \cdots & t_D^{1j}/d_1 & \cdots & t_D^{1n}/d_1 \\ \vdots & & \vdots & & \vdots \\ t_D^{i1}/d_i & \cdots & t_D^{ij}/d_i & \cdots & t_D^{in}/d_i \\ \vdots & & \vdots & & \vdots \\ t_D^{n1}/d_n & \cdots & t_D^{nj}/d_n & \cdots & t_D^{nn}/d_n \end{bmatrix} = \begin{bmatrix} t_D^{\alpha 11} & \cdots & t_D^{\alpha 1j} & \cdots & t_D^{\alpha 1n} \\ \vdots & & \vdots & & \vdots \\ t_D^{\alpha i1} & \cdots & t_D^{\alpha ij} & \cdots & t_D^{\alpha in} \\ \vdots & & \vdots & \ddots & \vdots \\ t_D^{\alpha n1} & \cdots & t_D^{\alpha nj} & \cdots & t_D^{\alpha nn} \end{bmatrix} \tag{19}$$

where:

$$d_i = \sum_{j=1}^{n} t_d^{ij}, \text{for } i = 1, 2, \ldots, n \tag{20}$$

The weighted supermatrix W_W is based on the integration of the unweighted matrix W into the normalized matrix of attribute influences T_D^α according to (17).

$$W_w = \begin{bmatrix} t_D^{\alpha 11} \times W^{11} & t_D^{\alpha 21} \times W^{12} & \cdots & \cdots & t_D^{\alpha n1} \times W^{1n} \\ t_D^{\alpha 12} \times W^{21} & t_D^{\alpha 22} \times W^{22} & \vdots & & \vdots \\ \vdots & \cdots & t_D^{\alpha ij} \times W^{ij} & \cdots & t_D^{\alpha nj} \times W^{in} \\ \vdots & & \vdots & \ddots & \vdots \\ t_D^{\alpha 1n} \times W^{n1} & t_D^{\alpha 2n} \times W^{n2} & \cdots & \cdots & t_D^{\alpha nn} \times W^{nn} \end{bmatrix} \tag{21}$$

Step 5.7. Computation of the limit supermatrix. The limit supermatrix is calculated by raising the weighted supermatrix W_W to a sufficient power k, until the supermatrix has converged to a long-term stable supermatrix. The vectors of the limit supermatrix represent the relative weights of each attribute with regards to the evaluation of the IDC location.

$$\lim_{k \to \infty} W_w^k \tag{22}$$

Step 5.8. Determination of the final weights of the alternatives. The final weights of the alternatives are found in the corresponding columns of the limit supermatrix. The alternative with the highest overall priority value is selected.

4. Case study and results

This section details the application of the proposed approaches for locating an International Distribution Center (IDC) in Europe. The process of selecting alternatives and determining the criteria values is described in Subsections 4.1 and 4.2, respectively. Subsections 4.3 and 4.4 focus on the application of ANP and DANP for international DC location selection. Subsection 4.4 provides a summary and comparison of the results obtained from ANP and DANP methodologies. The final subsection conducts a sensitivity analysis to assess the robustness of the selected approach.

4.1. Selection of alternatives for international DC location in Europe

Potential alternatives for international DC location are chosen using the Logistics Performance Index (LPI), an interactive benchmarking tool developed by the World Bank. Updated regularly, the LPI helps countries assess their trade logistics performance, identifying challenges and opportunities. According to the 2018 global ranking (Arvis et al., 2018), several countries rank highly on the LPI scale, including Germany (3.83), the Netherlands (3.74), France (3.84), Spain (4.02), and Italy (4.20) on a scale of 1 to 5. Logistics-intensive regions within these countries are evaluated as potential IDC locations.

More precisely, the selected alternatives (A) are (Fig. 4):

- A1. Germany: North Rhine-Westphalia (NRW) represents one of the most important logistics hubs in Europe. NRW plays a key role in the hinterland traffic of ZARA's seaports (Ports of Zeebrugge, Amsterdam, Rotterdam, and Antwerp) not only as a transit region, but also as a region of origin and destination.
- A2. The Netherlands: the South Holland region, with the Rotterdam logistics cluster, represents one of the central hubs for intercontinental maritime import and export flows to and from the European Union.
- A3. France: the Hauts-de-France region (formerly Northern France), and its capital Lille, are pivotal in the third-richest consumer area of the world.
- A4. Spain: the region of Aragon is characterized by its strategic location at the convergence of the main transportation routes: Madrid-Barcelona, and the Atlantic-Mediterranean corridor, and its connection to the South of France.
- A5. Italy: the Emilia-Romagna region represents a focal platform and gateway for freight traffic. It is located in one of the most productive areas of Europe.

The data collection process for each of the criteria considered in the model (Table 3) included the evaluation of relevant data sources from numerous databases of various organizations (Eurostat, World Bank, national statistical databases, real estate companies, port authorities, transport operators, international consultancy companies, etc.), as well as personal meetings with experts in the field of transport and logistics.

4.2. Determining the values of criteria for evaluation of international DC location

Values of selected criteria for each alternative are given in Table 5. Valuation of criteria is made as follows:

- C1. Ease of access to seaport measured as the volume of containers (million TEUs), data provided at national level.
- C2. Closeness to logistics hubs measured as the distance to logistics hub and number of logistics hubs in the area.
- C3. Logistics potential (industrial demand for logistics services/indirect businesses) measured as the amount of freight transported by road (million ton-kilometers).
- C4. Intensity of transport flows in relation to different modes of transport measured in % of traffic congestion).
- C5. Level of industry diversity, measured by the number of manufacturing companies.

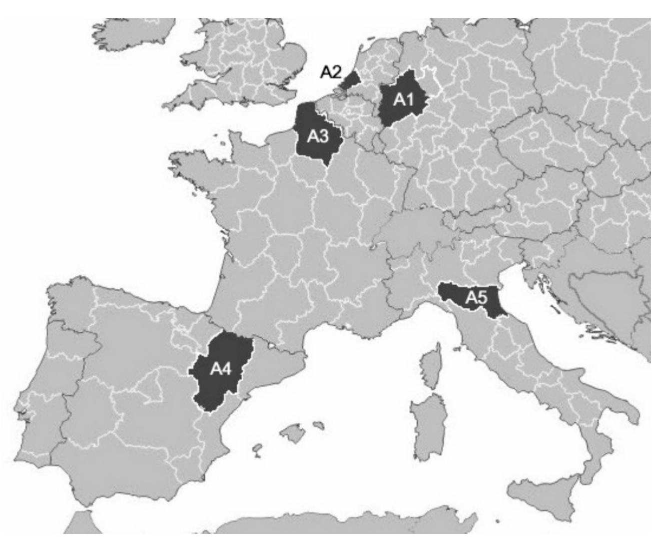

Fig. 4. Locations under study.

- C6. Number of carriers in the region (in this research figures are provided at national level).
- C7. Number of retailers in the region (data provided does not show the number of shops, but rather the number of companies).
- C8. Availability of highways within the region measured as number of connections if highways are available.
- C9. Connectivity of highways to logistics hubs – qualitative indicator based on the number of highways within the region.
- C10. Quality of highways, measured by the Road Quality Indicator, provided by the World Economic Forum.
- C11. The capacity of railroads for freight transportation, measured as the railway density (km of railway lines per 1000 km^2), by NUTS 2 regions.
- C12. Quality of railroad services (1(low) - 7(high)) based on the WEF (World Economic Forum) Executive Opinion Survey which includes the opinions of over 14,000 business leaders in 144 countries.
- C13. Level of intermodal transportation measured in the availability of different modes of transportation such as Very high (rail, airport, inland shipping, seaport, road and pipeline modes are available) or High (rail, seaport, airport, road, pipelines modes are available).
- C14. Cost of land acquisition measured in € per square meter.
- C15. Level of skilled labor (low (1) – high (5)) measured by the "Logistics Competence & Quality" of the World Bank on NUTS-0 level.
- C16. Availability of logistics educational programs measured in quality of educational programs based on ranking in Eduniversal Best Logistics Masters Ranking.
- C17. Labor regulations, measured by the Labor freedom index (0−100).
- C18. Labor availability, measured as the regional unemployment rate (%).
- C19. Labor costs measured in € per month.
- C20. Last mile, measured as the cost in € per 100 km.
- C21. Main haulage costs (per container), measured as the freight rates in euros (table shows average costs for export/ import to and from Shanghai).
- C22. Ease of loading/unloading, measured as the efficiency at the customs: speed, simplicity, predictability of formalities.
- C23. Level of supply chain fluidity, measured as the timeliness of shipments in reaching destination within the scheduled or expected delivery time.
- C24. Tax rate (Corporate (%).
- C25. Possibility of VAT deferment.

4.3. ANP for international DC location selection

Results of the execution of Steps 5.1 through 5.8 (Section 3.2) are given. Table A1 shows the unweighted supermatrix, Table A2 the weighted supermatrix and Table A3 the limit supermatrix containing dimensions and criteria (see Tables in Appendix A). Expert Choice™ software was used to obtain the eigenvectors and consistency tests, and Excel for the calculation of the unweighted, weighted, and limit matrices. It can be seen that the most important criteria for evaluating the location of an IDC are C23 (9%), C7 (7.34%), C6 (7.13%), and C5 (6.13%).

The eigenvectors of the five alternatives for the 25 criteria were obtained from Table 5. Results are provided in Table 6. The final weights of the alternatives can be extracted from the vector of priorities, which was aggregated from Table A3, and the vector of priorities provided in Table 6, as seen in (23).

The results obtained from the model (refer to Eq. 23) indicate the ranking of the preferred alternatives as follows: A1 (North Rhine-Westphalia) > A4 (Aragon) > A3 (Hauts-de-France) > A5 (Emilia-Romagna) > A2 (South Holland) (also depicted in Fig. 5). This ranking highlights North Rhine-Westphalia as the most favorable location for the International Distribution Center (IDC), followed by Aragon, Hauts-de-

Table 5
Information on the criteria for each of the alternatives considered (source: adapted from Zaragoza Logistics Center, ZLC (2018).

D	C	A1 (North Rhine-Westphalia)	A2 (South Holland)	A3 (Hauts-de-France)	A4 (Aragon)	A5 (Emilia-Romagna)
D1	C1	14.7	13.88	5.9	17	10.86
	C2	3 logistics hubs in a 495 km radius	5 logistics hubs in a radius of 134 km	5 logistics hubs in a radius of 300 km	3 logistics hubs in a radius of 150 km	3 logistics hubs in a radius of 200 km
	C3	311,869	44,418	181,400	249,555	137,986
D2	C4	19	19	20	13	18
	C5	148,551	1089	133,778	292,302	284,136
	C6	34,537	12,000	119,000	58,026	90,000
	C7	597	441	392	451	285
D3	C8	5 connections	2 connections	4 connections	6 connections	2 connections
	C9	Very high	Medium	High	Very High	Medium
	C10	5.30	6.40	5.40	5.70	4.40
	C11	≥ 120	98	63	38	63
	C12	4.37	4.21	4.00	3.84	3.85
	C13	Very high	Very high	High	High	High
	C14	100	202.5	51.56	92.5	100.5
D4	C15	4.31	4.09	3.84	3.8	3.66
	C16	Yes (Ranking 52nd Business School)	Yes (Ranking 21st Business School)	Yes (Ranking 5th Business School)	Yes (ranking 1st Business School)	Yes (Ranking 3th Business School)
	C17	53	60	45	58	51
	C18	6.3	6.3	8.8	12.4	5.3
	C19	4174	4002	4652	3029	3121
D5	C20	120	120	140	213	215
	C21	694 / 881	469 / 781	737 / 774	345 / 765	525 / 1069
D6	C22	4.09	3.92	3.59	3.62	3.47
	C23	4.39	4.25	4.15	4.06	4.13
D7	C24	30	25	26.50	25	24
	C25	Yes	Yes	Yes	Yes	Yes

Table 6
Eigenvectors of the location alternatives according to the criteria.

D	C	A1	A2	A3	A4	A5
Regional logistics system attractiveness (D1)	Ease of access to seaport (C1)	0.2358	0.2226	0.0946	0.2727	0.1742
	Closeness to logistics hubs (C2)	0.1212	0.3030	0.1818	0.2121	0.1818
	Logistics potential of region (C3)	0.3371	0.0480	0.1961	0.2697	0.1491
Industry (D2)	Intensity of transport flows in relation to different modes (C4)	0.2135	0.2135	0.2247	0.1461	0.2022
	Level of industry diversity (C5)	0.1728	0.0013	0.1556	0.3399	0.3304
	Number of carriers in the region (C6)	0.1101	0.0383	0.3795	0.1851	0.2870
	Number of retailers in the region (C7)	0.2756	0.2036	0.1810	0.2082	0.1316
Infrastructure (D3)	Availability of highways within the region (C8)	0.2632	0.1053	0.2105	0.3158	0.1053
	Connectivity of highways to logistics hubs (C9)	0.2500	0.1500	0.2000	0.2500	0.1500
	Quality of highways (C10)	0.1949	0.2353	0.1985	0.2096	0.1618
	Capacity of railroads for freight transportation (C11)	0.2941	0.2353	0.1765	0.1176	0.1765
	Quality of railroad services (C12)	0.2156	0.2077	0.1973	0.1894	0.1899
	Level of intermodal transportation (C13)	0.2273	0.2273	0.1818	0.1818	0.1818
	Cost of land acquisition (square meter) (C14)	0.2045	0.1571	0.2244	0.2095	0.2045
Workforce (D4)	Level of skilled labor (C15)	0.2188	0.2076	0.1949	0.1929	0.1858
	Availability of logistics educational programs (C16)	0.1739	0.1739	0.2174	0.2174	0.2174
	Labor regulations (C17)	0.1985	0.2247	0.1685	0.2172	0.1910
	Labor availability (C18)	0.1426	0.1426	0.2384	0.3337	0.1426
	Labor costs (€/month) (C19)	0.2199	0.2109	0.2451	0.1596	0.1645
Transport costs (D5)	Last mile (C20)	0.2632	0.2632	0.1053	0.2105	0.1579
	Main haulage costs (per container) (C21)	0.2248	0.1717	0.2163	0.1589	0.2281
Global shipments (D6)	Ease of loading/unloading (C22)	0.2188	0.2097	0.1921	0.1937	0.1857
	Level of supply chain fluidity (C23)	0.2092	0.2026	0.1978	0.1935	0.1969
Taxes (D7)	Tax rate (C24)	0.2299	0.1916	0.2031	0.1916	0.1839
	Possibility of VAT deferment (C25)	0.2000	0.2000	0.2000	0.2000	0.2000

France, Emilia-Romagna, and South Holland.

4.4. DANP for international DC location selection

According to the evaluation framework (Fig. 3), the combined DANP approach includes the modification of pairwise comparisons and the formation of the unweighted supermatrix (Table B1 of Appendix B) based on the direct influence matrix where pairwise comparisons are carried out for the entire problem rather than just at the cluster level. The weighted supermatrix (Table B2 of Appendix B) is obtained by integrating the unweighted supermatrix and the total influence matrix. Raising the weighted supermatrix to the limiting power leads to the final priorities (Table B3 of Appendix B). The total influence matrix and the network relationship map are shown in Fig. 6 and Table 7. It can be seen that all perspectives of the IDC location selection problem are interdependent. The computations were carried out in Excel.

The causal diagram depicting the total relationship is illustrated in Fig. 7, derived from the values presented in Table 8, which summarize the influences given and received across various criteria.

Dimensions/criteria with positive r_i-c_i values are known as net causers (Chen et al., 2011). Positive values of r_i-c_i imply that a specific dimension/criterion has a significant impact on other dimensions/

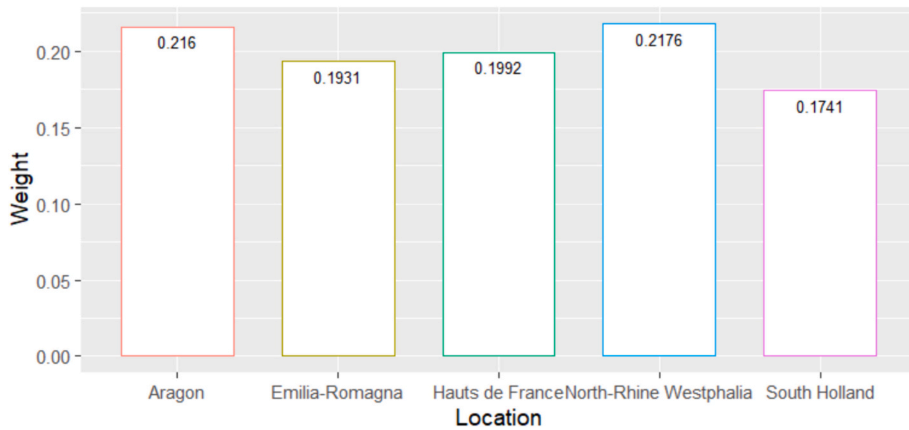

Fig. 5. Total ranking of alternatives using the ANP approach.

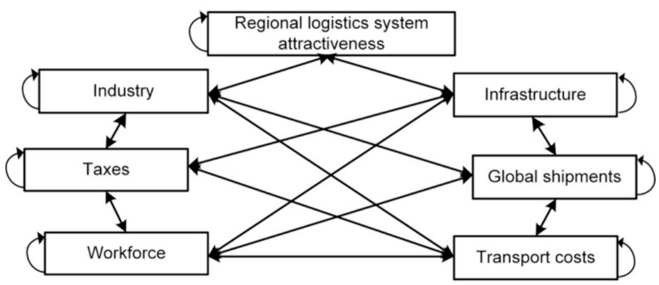

Fig. 6. Relationships between dimensions.

criteria. Negative r_i-c_i value characterizes those dimensions/criteria that are highly dependent on other dimensions/criteria. Dimensions/criteria with negative r_i-c_i value are known as net receivers. The r_i-c_i value reflects the degree of relationship between dimensions/criteria. A higher r_i-c_i implies a stronger relationship between a pair of dimensions/criteria. The highest r_i-c_i value is found for dimension D7 (Taxes). This dimension has a strong unidirectional impact on all other dimensions. Tax policy contributes significantly to all other aspects of DC location selection, directly, as in the case of the attractiveness of the regional logistics system (D1), transport costs (D5), industry (D2) or global shipments (D6), or indirectly, as in the case of the workforce (D4) or infrastructure (D3). Developed infrastructure (D3) positively influences the attractiveness of the regional logistics system (D1), transport costs (D5), global shipments (D6) and workforce (D4). Apart from D7 and D3, all other dimensions represent net receivers, which means that they are under the strong influence of other dimensions. On the other hand, the attractiveness of the regional logistics system (D1) has the highest r_i-c_i value since it has the strongest influence (11.275 in $r_{D1+}c_{D1}$). This implies that D1 is the most influencing aspect of the DC location selection problem, whereas D7 has the weakest relationship with other dimensions (8.194 in total sum $r_{D7+}c_{D7}$).

Similarly, at the level of the regional logistics system attractiveness (D1), criterion C4 related to the intensity of transport flows is the first in terms of the index of the strength of influence given and received. The highest r_i-c_i value is given to criteria C3, which represents the logistics potential of the region. The strongest influence given and received in D2 (Industry) is given to criterion C7 (Number of retailers in the region), whereas C5 (industry diversity) is the main net causal criterion. Criterion C13 (Level of intermodal transportation) has the highest impact on the other criteria in dimension D3 (Infrastructure) compared to criterion C14 which has the lowest (the least sum of r_i-c_i). Criterion C12 (Quality of railroad services) has the greatest direct impact on the other criteria

$$
\begin{array}{c}
 \\ A1 \\ A2 \\ A3 \\ A4 \\ A5
\end{array}
\begin{array}{ccccccccccccccccccccccccc}
C1 & C2 & C3 & C4 & C5 & C6 & C7 & C8 & C9 & C10 & C11 & C12 & C13 & C14 & C15 & C16 & C17 & C18 & C19 & C20 & C21 & C22 & C23 & C24 & C25 \\
\end{array}
$$

$$
\begin{bmatrix}
0.2358 & 0.1212 & 0.3371 & 0.2135 & 0.1728 & 0.1101 & 0.2756 & 0.2632 & 0.2500 & 0.1949 & 0.2941 & 0.2156 & 0.2273 & 0.2045 & 0.2188 & 0.1739 & 0.1985 & 0.1426 & 0.2199 & 0.2632 & 0.2248 & 0.2188 & 0.2092 & 0.2299 & 0.2000 \\
0.2226 & 0.3030 & 0.0480 & 0.2135 & 0.0013 & 0.0383 & 0.2036 & 0.1053 & 0.1500 & 0.2353 & 0.2353 & 0.2077 & 0.2273 & 0.1571 & 0.2076 & 0.1739 & 0.2247 & 0.1426 & 0.2109 & 0.2632 & 0.1717 & 0.2097 & 0.2026 & 0.1916 & 0.2000 \\
0.0946 & 0.1818 & 0.1961 & 0.2247 & 0.1556 & 0.3795 & 0.1810 & 0.2105 & 0.2000 & 0.1985 & 0.1765 & 0.1973 & 0.1818 & 0.2244 & 0.1949 & 0.2174 & 0.1685 & 0.2384 & 0.2451 & 0.1053 & 0.2163 & 0.1921 & 0.1978 & 0.2031 & 0.2000 \\
0.2727 & 0.2121 & 0.2697 & 0.1461 & 0.3399 & 0.1851 & 0.2082 & 0.3158 & 0.2500 & 0.2096 & 0.1176 & 0.1894 & 0.1818 & 0.2095 & 0.1929 & 0.2174 & 0.2172 & 0.3337 & 0.1596 & 0.2105 & 0.1589 & 0.1937 & 0.1935 & 0.1916 & 0.2000 \\
0.1742 & 0.1818 & 0.1491 & 0.2022 & 0.3304 & 0.2870 & 0.1316 & 0.1053 & 0.1500 & 0.1618 & 0.1765 & 0.1899 & 0.1818 & 0.2045 & 0.1858 & 0.2174 & 0.1910 & 0.1426 & 0.1645 & 0.1579 & 0.2281 & 0.1857 & 0.1969 & 0.1839 & 0.2000
\end{bmatrix}
*
\begin{bmatrix}
0.0553 \\ 0.0472 \\ 0.0546 \\ 0.0490 \\ 0.0613 \\ 0.0713 \\ 0.0734 \\ 0.0320 \\ 0.0315 \\ 0.0256 \\ 0.0261 \\ 0.0263 \\ 0.0432 \\ 0.0213 \\ 0.0133 \\ 0.0184 \\ 0.0171 \\ 0.0155 \\ 0.0164 \\ 0.0481 \\ 0.0395 \\ 0.0334 \\ 0.0900 \\ 0.0503 \\ 0.0402
\end{bmatrix}
=
\begin{bmatrix}
0.2176 \\ 0.1741 \\ 0.1992 \\ 0.2160 \\ 0.1931
\end{bmatrix}
\quad (23)
$$

Table 7
Total influence matrix: seven dimensions.

	D1	D2	D3	D4	D5	D6	D7	Row sum(r_i)	Column sum (c_i)	$r_i + c_i$	r_i-c_i
D1	0.765	0.859	0.773	0.736	0.819	0.817	0.543	5.313	5.962	11.275	−0.649
D2	0.957	0.763	0.811	0.796	0.857	0.837	0.591	5.612	5.631	11.243	−0.018
D3	0.971	0.901	0.667	0.755	0.887	0.850	0.573	5.604	4.906	10.510	0.699
D4	0.737	0.719	0.572	0.489	0.662	0.630	0.434	4.243	4.744	8.987	−0.501
D5	0.859	0.813	0.709	0.673	0.648	0.763	0.511	4.975	5.393	10.368	−0.418
D6	0.886	0.825	0.736	0.680	0.801	0.649	0.539	5.117	5.241	10.358	−0.124
D7	0.786	0.752	0.638	0.616	0.718	0.694	0.399	4.603	3.591	8.194	1.012

(r_{C12}-c_{C12} = 0.682). Within dimension D4 (Workforce), criterion C19 (Labor costs) represents the criterion with the highest impact on the other criteria. The main net causer is criterion C17 (Labor regulations). Dimension D5 (Transport costs) is characterized by a strong impact of criterion C21 (Main haulage costs per container). Likewise, in the case of D6 (Global shipments), criterion C22 (Easy of loading and unloading) has a significant impact on the level of supply chain fluidity (C23). In the case of D7 (Taxes), criterion C24 (Tax rate) represents the most influential factor.

The relative importance of dimensions and criteria obtained by DANP is presented in Table 9. The most important dimension for IDC location selection is D1 (Regional logistics system attractiveness), while the least important is dimension D7 (Taxes). Regarding individual criteria, the five most important are criteria C20 (Last mile), C23 (Level of supply chain fluidity), C22 (Ease of loading/unloading), C6 (Number of carriers in the region) and C21 (Main haulage costs (per container)). On the other hand, criterion C8 (Availability of highways within the region), C16 (Availability of logistics educational programs), C17 (Labor

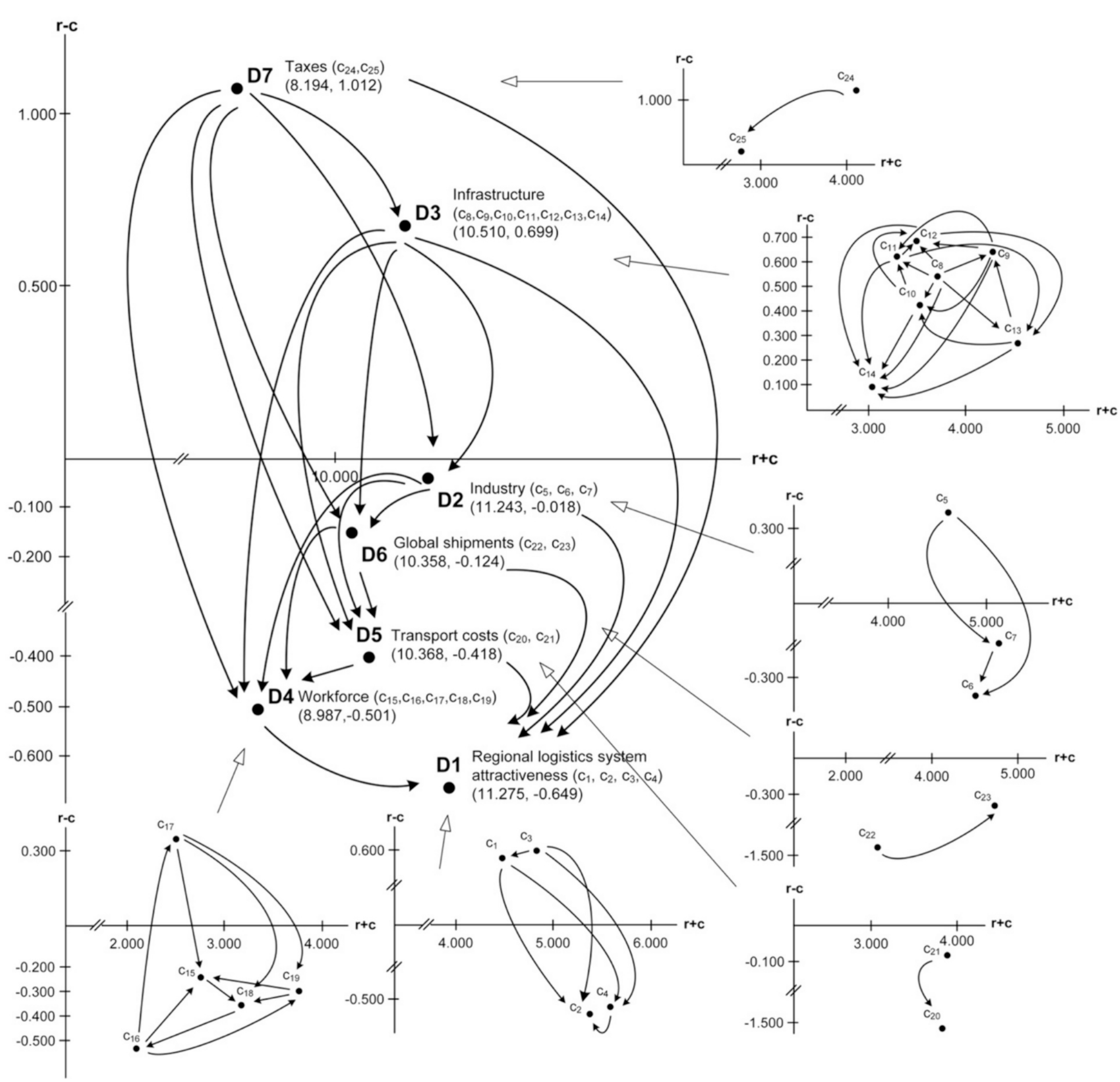

Fig. 7. Causal diagram of total relationships.

Table 8
Sum of given and received influences on criteria.

Dimension (i)/Criteria (i)	Row sum (r_i)	Column sum (c_i)	$r_i + c_i$	r_i-c_i
Regional logistics system attractiveness (D1)	**5.313**	**5.962**	**11.275**	**−0.649**
Ease of access to seaport (C1)	2.605	2.013	4.618	0.593
Closeness to logistics hubs (C2)	2.395	2.939	5.334	−0.544
Logistics potential of region (C3)	2.694	2.092	4.786	0.601
Intensity of transport flows in relation to different modes of transport (C4)	2.429	2.964	5.392	−0.535
Industry (D2)	**5.612**	**5.631**	**11.243**	**−0.018**
Level of industry diversity (C5)	2.474	2.164	4.638	0.311
Number of carriers in the region (C6)	2.336	2.655	4.991	−0.319
Number of retailers in the region (C7)	2.482	2.617	5.100	−0.135
Infrastructure (D3)	**5.604**	**4.906**	**10.510**	**0.699**
Availability of highways within the region (C8)	2.163	1.621	3.784	0.543
Connectivity of highways to logistics hubs (C9)	2.496	1.861	4.357	0.635
Quality of highways (C10)	2.094	1.681	3.775	0.413
Capacity of railroads for freight transportation (C11)	2.069	1.450	3.519	0.618
Quality of railroad services (C12)	2.104	1.423	3.527	0.682
Level of intermodal transportation (C13)	2.434	2.173	4.608	0.261
Cost of land acquisition (square meter) (C14)	1.593	1.495	3.088	0.098
Workforce (D4)	**4.243**	**4.744**	**8.987**	**−0.501**
Level of skilled labor (C15)	1.300	1.564	2.864	−0.264
Availability of logistics educational programs (C16)	0.769	1.293	2.061	−0.524
Labor regulations (C17)	1.473	1.158	2.631	0.314
Labor availability (C18)	1.428	1.783	3.210	−0.355
Labor costs (€/month) (C19)	1.704	2.009	3.714	−0.305
Transport costs (D5)	**4.975**	**5.393**	**10.368**	**−0.418**
Last mile (C20)	1.080	2.642	3.723	−1.562
Main haulage costs (per container) (C21)	1.851	1.895	3.746	−0.044
Global shipments (D6)	**5.117**	**5.241**	**10.358**	**−0.124**
Ease of loading/unloading (C22)	0.681	1.895	2.810	−1.449
Level of supply chain fluidity (C23)	2.254	2.640	4.894	−0.386
Taxes (D7)	**4.603**	**3.591**	**8.194**	**1.012**
Tax rate (C24)	2.638	1.480	4.118	1.158
Possibility of VAT deferment (C25)	1.452	1.256	2.709	0.196

regulations), C11 (Capacity of railroads for freight transportation), C14 (Cost of land acquisition (square meter), and C12 (Quality of railroad services) represent the least important criteria.

Now, considering the value of alternatives against each criterion, the ranking of alternatives can be calculated. Fig. 8 represents the relative ranking of the alternatives obtained using the DANP approach.

4.5. Comparison of results obtained by ANP and DANP

Fig. 9 presents the combined results of both approaches. Interestingly, both approaches yielded the same order of preference for the alternatives, albeit with different weighting. The ranking remains consistent: North-Rhine Westphalia (A1) > Aragon (A4) > Hauts-de-France (A3) > Emilia-Romagna (A5) > South Holland (A2). The quantification of these preferences is as follows: 0.2176 (ANP) > 0.2151 (DANP) for A1, 0.2160 (ANP) > 0.2095 (DANP) for A4, 0.1992 (ANP) > 0.1984 (DANP) for A3, 0.1931 (ANP) > 0.1933 (DANP) for A5, and 0.1741 (ANP) > 0.1837 (DANP) for A2.

The same ranking of alternatives was obtained; however, different criteria were identified as the most important (Fig. 10): (i) C23 (Level of supply chain fluidity), C7 (Number of retailers in the region), C6 (Number of carriers in the region), C5 (Level of industry diversity), and C1 (Ease of access to seaport) (0.0900 > 0.0734 > 0.0713 > 0.0613 > 0.0553) for the ANP approach. (ii) C20 (Last mile), C23 (Level of supply chain fluidity), C22 (Ease of loading/unloading), C6 (Number of carriers in the region) and C21 (Main haulage costs (per container)) (0.095 > 0.094 > 0.073 > 0.068 > 0.065) were reported as the most important criteria for the DANP approach. Only C6 and C23 are among the top five in order of importance in both approaches.

The analysis also showed a different ranking of importance of the dimensions considered (Fig. 11): (i) D1 (0.1566) > D3 (0.1525) > D6 (0.1458) > D5 (0.1442) > D2 (0.1386) > D7 (0.1327) > D4 (0.1296) for the ANP approach; and (ii) D1 (0.1789) > D2 (0.1748) > D6 (0.1668) > D5 (0.1609) > D3 (0.1196) > D4 (0.1001) > D7 (0.0958) for the DANP approach. In both approaches, D1 (regional logistics system attractiveness), D6 (global shipments) and D5 (transport costs) have the same order of importance (1st, 3rd, 4th positions) in the ranking.

Table 9
Relative ranking of dimensions and criteria obtained by $lim_{n\to\infty}(W^{\alpha})^n$.

Dimension (D)	Relative weight of dimension	Criteria (C)	Relative weight of criteria
Regional logistics system attractiveness (D1)	0.180	Ease of access to seaport (C1)	0.035
		Closeness to logistics hubs (C2)	0.052
		Logistics potential of region (industrial demand for logistics services/indirect businesses) (C3)	0.038
		Intensity of transport flows in relation to different modes of transport (traffic congestion) C4)	0.055
Industry (D2)	0.175	Level of industry diversity (C5)	0.046
		Number of carriers in the region (C6)	0.068
		Number of retailers in the region (C7)	0.061
Infrastructure (D3)	0.120	Availability of highways within the region (C8)	0.017
		Connectivity of highways to logistics hubs (C9)	0.019
		Quality of highways (C10)	0.018
		Capacity of railroads for freight transportation (C11)	0.018
		Quality of railroad services (C12)	0.014
		Level of intermodal transportation (C13)	0.024
		Cost of land acquisition (square meter) (C14)	0.014
Workforce (D4)	0.100	Level of skilled labor (C15)	0.020
		Availability of logistics educational programs (C16)	0.017
		Labor regulations (C17)	0.015
		Labor availability (C18)	0.023
		Labor costs (€/month) (C19)	0.026
Transport costs (D5)	0.161	Last mile (C20)	0.095
		Main haulage costs (per container) (C21)	0.065
Global shipments (D6)	0.167	Ease of loading/unloading (C22)	0.073
		Level of supply chain fluidity (C23)	0.094
Taxes (D7)	0.096	Tax rate (C24)	0.051
		Possibility of VAT deferment (C25)	0.044

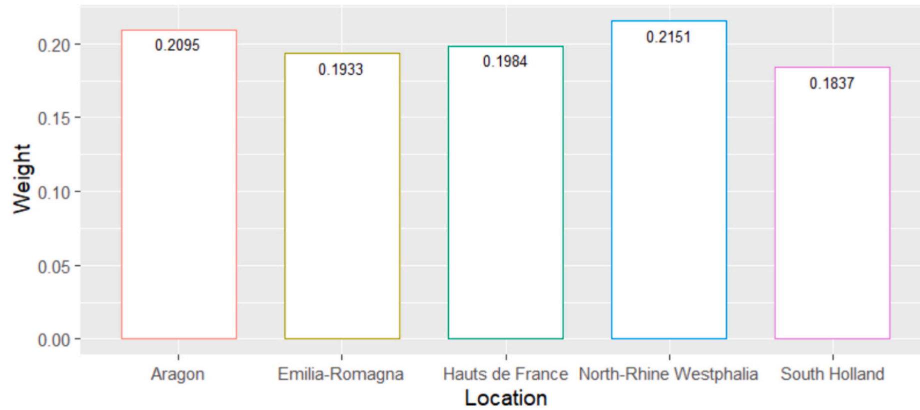

Fig. 8. Total ranking of alternatives by DANP approach.

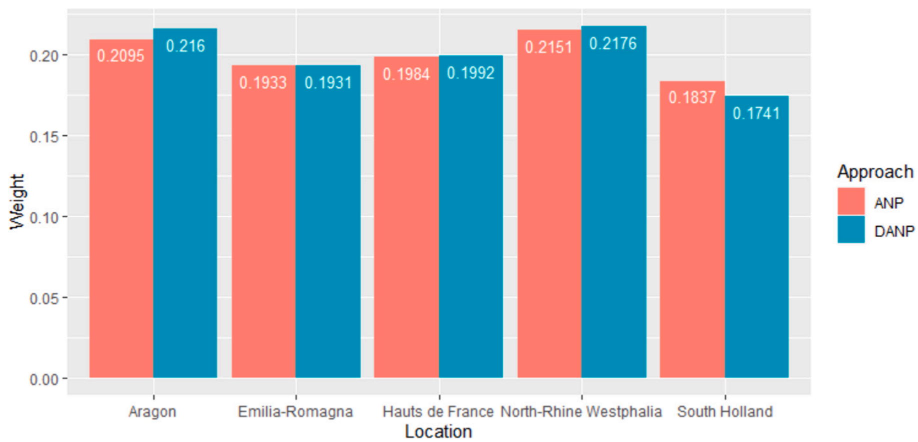

Fig. 9. Total ranking of alternatives by ANP and DANP approach.

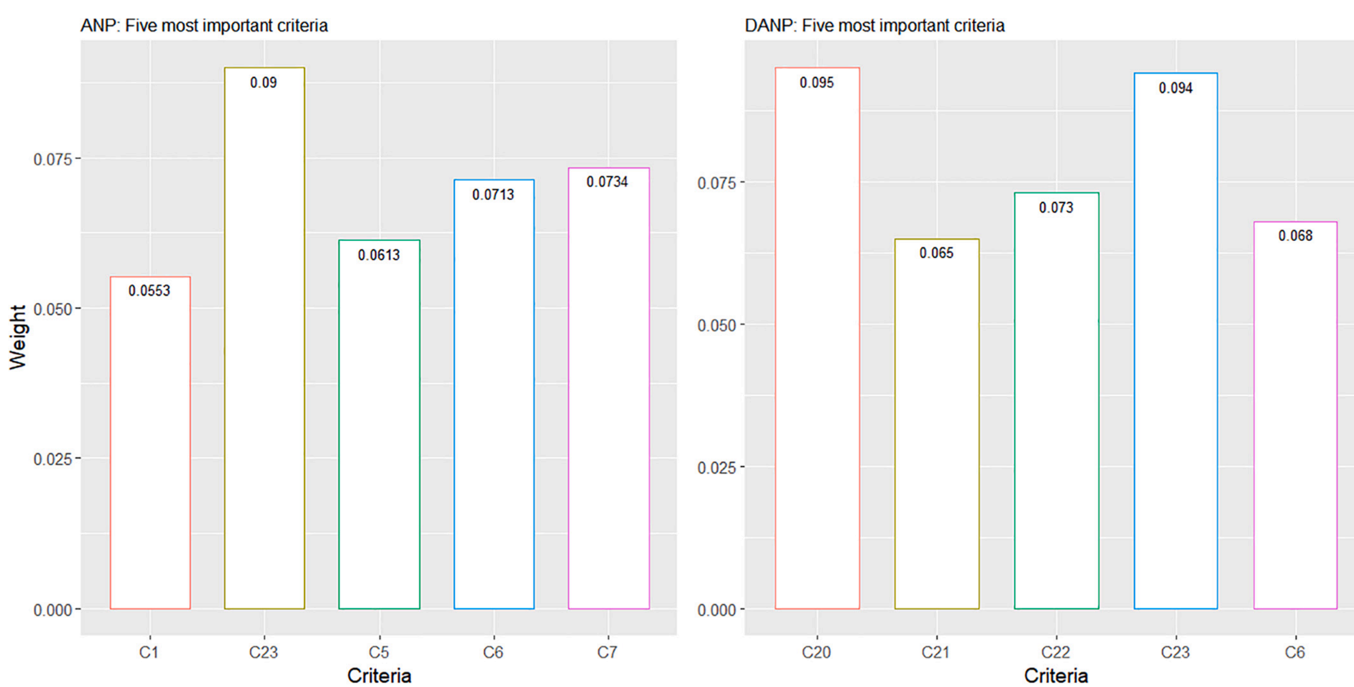

Fig. 10. Total ranking of the most important criteria by ANP and DANP approach.

4.6. Sensitivity analysis

The stability and validity of the research findings are ensured by a sensitivity analysis. The sensitivity analysis is performed on five scenarios simulating a random sample of $n = 1000$ cases. The first three scenarios include varying the criteria weights by $+/-$ 10, 20 and 50%, respectively. The fourth and fifth scenarios include increasing and decreasing the weights of the five most important criteria (Fig. 10) by 50%, respectively. The outcomes derived from both ANP and DNP methods demonstrate consistency in all scenarios. The ranking of the alternatives remains the same in all cases. The results of the sensitivity analysis for all scenarios can be seen in Table 10.

Table 10
Results of the sensitivity analysis.

Scenario	Applied approach	Alternatives				
		A1	A2	A3	A4	A5
Scenario 1	ANP	0.2176	0.1741	0.1992	0.2160	0.1931
	DANP	0.2151	0.1837	0.1983	0.2095	0.1933
Scenario 2	ANP	0.2177	0.1740	0.1992	0.2160	0.1931
	DANP	0.2151	0.1836	0.1984	0.2095	0.1934
Scenario 3	ANP	0.2177	0.1744	0.1990	0.2158	0.1931
	DANP	0.2152	0.1837	0.1984	0.2094	0.1932
Scenario 4	ANP	0.2134	0.1648	0.2014	0.2205	0.1999
	DANP	0.2565	0.2203	0.2396	0.2471	0.2340
Scenario 5	ANP	0.2164	0.1713	0.1997	0.2174	0.1952
	DANP	0.1737	0.1471	0.1572	0.1718	0.1526

5. Discussion

This paper proposes an application of ANP and DANP to select the preferred location of an IDC in five regions with the highest intensity of logistics activities in Europe: North-Rhine Westphalia region (Germany), South Holland region (The Netherlands), Hauts-de-France region (France), Aragon region (Spain), and Emilia-Romagna region (Italy).

The initial model was composed of 10 dimensions and 66 criteria. The analysis provided a final set of 25 criteria considered as the most important for selecting the location of a new IDC grouped into 7 dimensions (regional logistics system attractiveness, industry, infrastructure, workforce, transport costs, global shipment, and taxes). It is pertinent to acknowledge that while sustainability has garnered increasing attention as a focal point in certain methodologies (e.g., Ayadi et al., 2021; Kumar & Anbanandam, 2020), particularly in the assessment of the impact of transport activities (Agrebi & Abed, 2021; Pham et al., 2017), it has been deliberately excluded from the initial array of dimensions by experts engaged in this study, as per the methodology discussed in Section 3.2.1, within the context of IDC location.

Of the 25 criteria used, 9 of them were proposed by the experts who participated in the evaluation in the framework of an IDC location, and the rest were identified from relevant literature (Table 2). The new criteria identified are as follows: logistics potential of the region, number of carriers in the region, number of retailers in the region, availability of logistics educational programs, labor regulations, main haulage costs (per container), ease of loading/unloading, level of supply chain fluidity, and the possibility of VAT deferment.

The results showed different priorities of the criteria with different orders of importance in both approaches. Only the level of supply chain fluidity (C23), and the number of carriers in the region (C6) were among the five most important. However, in terms of dimensions, both approaches considered regional logistics system attractiveness (D1), global shipments (D6) and transport costs (D5) to be the first, third and fourth most important, respectively. Transport costs were also considered as a key dimension in Zhang and Yin (2017).

Both approaches ranked the region of North-Rhine Westphalia (A1) as the most preferable alternative for an IDC location followed closely by the Aragon region (A4), while the South Holland region (A2) was the least preferable location for an IDC.

North Rhine-Westphalia is dominant from the aspect of the level of supply chain fluidity (C23), and the number of retailers in the region (C7) and is also very competitive concerning last mile costs (C20). Compared to this alternative, the Aragon region ranked preferred regarding some criteria: C1 (ease of access to seaport), C2 (closeness to logistics hubs), C5 (level of industry diversity), C6 (number of carriers in the region), C8 (availability of highways within the region), C10 (quality of highways), C14 (cost of land acquisition), C16 (availability of logistics educational programs), C17 (labor regulations) and C18 (labor availability), but it must improve in terms of C3 (logistics potential of the

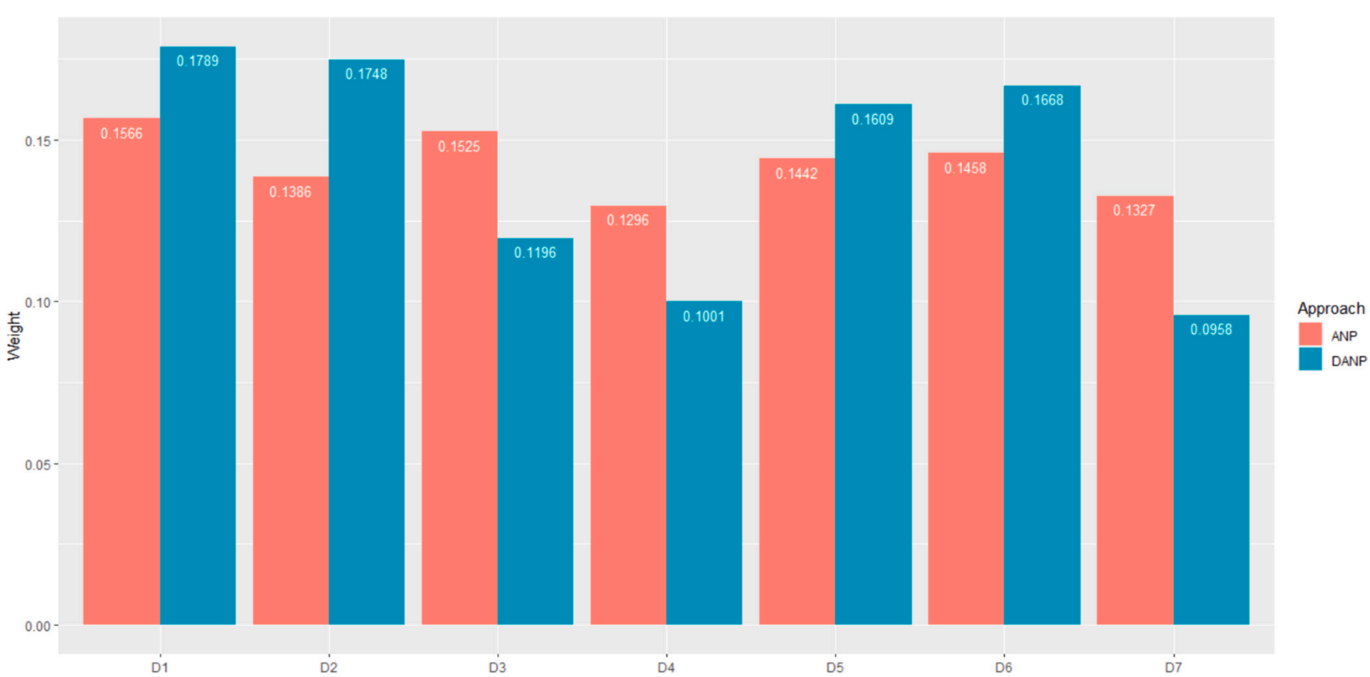

Fig. 11. Total ranking of dimensions by ANP and DANP approach.

region), C4 (intensity of transport flows), C7 (number of retailers in the region), C11 (capacity of railroads for freight transportation), C12 (quality of railroad services), C13 (level of intermodal transportation), C15 (level of skilled labor), C19 (labor costs), C20 (last mile costs), C21 (main haulage costs), C22 (ease of loading/ unloading), C23 (level of supply chain fluidity), and C24 (tax rate). Both alternatives are equally preferred in terms of C9 (connectivity of highways to logistics hubs) and C25 (possibility of VAT deferment).

South Holland region, despite being the least preferred location option for an IDC in our analysis, ranked first in relation to some criteria: C2, C10, and C17, and obtained the same importance as A1 in C4. Hauts-de-France region (A3) obtained the highest score regarding the other alternatives in C4, C6, C14, and C19. Emilia-Romagna (A5) is dominant in C21 regarding the other alternatives.

From a theoretical viewpoint, this paper contributes to the research on the DC location by identifying nine new criteria already discussed in this section. In addition, the comparison of ANP and DANP has not been performed before in this context. The decision-making framework proposed in this paper and the results of the analysis are of great importance to decision-makers. By considering potential location sites for their IDC, decision-makers can define which locations are most preferable and which can be less important. This ranking facilitates decision-makers in judiciously allocating resources and financial investments effectively. Furthermore, the approach provides a general decision-making framework that incorporates a comprehensive set of criteria which can be used by managers to plan, analyze, and calculate the relative importance of alternative locations for their IDC positioning.

The results obtained allow the regions analyzed to gain knowledge of their performance in terms of locating an IDC; the methodology illustrates how one region can be more competitive than another based on different criteria. The process extracts knowledge that is fundamental for the improvement of the regions in the seven dimensions analyzed.

In terms of robustness, managers can rely on both ANP and DANP methods, however, in the case of DANP, managers can rely on a higher level of comprehensiveness of the decision-making process compared to the ANP technique.

6. Practical implications

The practical importance of this study is multifaceted. The proposed approach offers stakeholders a decision-making framework for planning, analyzing, and prioritizing alternative IDC locations.

The study identifies a set of 25 most important criteria, grouped into seven dimensions which are essential for the selection of an optimal location for an International Distribution Center (IDC) in Europe. A comprehensive analysis including five logistically most intensive regions provides valuable insights for stakeholders involved in IDC location decision making.

Ranking of criteria and alternative locations help decision-makers to efficiently allocate resources and financial investments based on the relative importance of alternative locations.

From the aspect of policy making, the approach provides guidelines for implementing targeted policies and measures to improve specific criteria in different regions. Recommendations may span from enhancing infrastructure and workforce to taxation policies based on identified criteria. In this way, policy makers may understand and define a set of measures to improve the performance and competitiveness of specific regions for attracting IDCs. For example, within dimension D1 (Attractiveness of the regional logistics system), the Public Administration should focus on improving the ease of access to the seaport (C1) in the Hauts-de-France region. In dimension D3 (Infrastructure), actions should focus on improving the availability of highways (C8) and their connectivity to logistics hubs (C9) in the South Holland and Emilia-Romagna regions, investing in highways to improve their quality (C10) in the Emilia-Romagna region, and improving the capacity of railroads for freight transport (C11) in the Hauts-de-France region. Action could also be taken on D4 (Workforce) by supporting educational programs on logistics (C16) in North Rhine-Westphalia and the South Holland region and improving labor regulations (C17) in the Hauts-de-France region. Also, in D7 (Taxation), the Emilia-Romagna region can act on improving the tax rate for companies.

Finally, the study offers reliable decision-making support tools for IDC location selection. The DANP method, in particular, offers a higher level of comprehensiveness in the decision-making process compared to ANP, enhancing its utility for managers seeking a robust approach in complex decision scenarios.

7. Conclusion and further research

One of the key factors in global logistics operations is the location of the IDC because of the impact on costs and delivery times. This paper contributes to literature by providing a decision-making framework for prioritizing the location of distribution centers in Europe, to guide the decision-making process of stakeholders and policy makers involved in the selection of DC locations. Two different approaches have been used: ANP and DANP. Managers should note that the results of this analysis may change depending on the situation related to the 25 criteria considered in the evaluation model. The research carried out provides some practical implications that should facilitate the process of the IDC location problem solving for decision makers: (i) the identification of the main dimensions and criteria to be used in the evaluation of an IDC location in Europe; (ii) the development of two multicriteria approaches, based on ANP and DANP to evaluate the problem; and (iii) the application of both approaches in five locations in Europe.

This research has some limitations: the ranking of the alternatives is very close, which can be related to the number of alternative locations. In addition, there is vagueness and imprecision in human judgments. In future work, additional locations will be explored, and fuzziness and fuzzy randomness will be applied in the selection of the best IDC location. Additional social criteria may be considered, such as the quality of life of the territory. The final model was evaluated by 5 of the 15 participating experts, which implies that there might have been small variations in the criteria weights. Nevertheless, the sensitivity analysis carried out ensured the stability and validity of the results.

The final model does not consider sustainability as one of the criteria, despite this being a global logistics trend. This may be due to the fact that the experts participating in the study considered minimizing costs as the main objective. Sustainability may include additional investments that may increase costs in the short term. Decision-makers may have perceived the sustainability dimension as contradictory to efficiency or profitability.

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CRediT authorship contribution statement

Victoria Muerza: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Milos Milenkovic:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Emilio Larrodé:** Supervision, Validation, Writing – review & editing. **Nebojsa Bojovic:** Supervision, Validation, Writing – review & editing.

Declaration of competing interest

None.

Data availability

Not applicable.

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Appendix A. Supplementary data

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