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A Recommendation System Supporting the Implementation of Sustainable Risk Management Measures in Airport Operations

Silvia Carpitella [1,*], Bruno Brentan [2], Antonella Certa [3] and Joaquín Izquierdo [4]

[1] Department of Manufacturing Systems Engineering and Management, College of Engineering and Computer Science, California State University Northridge, 18111 Nordhoff Street, Northridge, CA 91330, USA
[2] School of Engineering, Federal University of Minas Gerais (UFMG), Belo Horizonte 31270-901, Brazil; brentan@ehr.ufmg.br
[3] Department of Engineering, University of Palermo, Viale delle Scienze, 90128 Palermo, Italy; antonella.certa@unipa.it
[4] Instituto Universitario de Matemática Multidisciplinar, Universitat Politècnica de València, Cno. de Vera s/n, 46022 Valencia, Spain; jizquier@upv.es
* Correspondence: silvia.carpitella@csun.edu

Abstract: This paper introduces a recommendation system aimed at enhancing the sustainable process of risk management within airport operations, with a special focus on Occupational Stress Risks (OSRs). The recommendation system is implemented via a flexible Python code that offers seamless integration into various operational contexts. It leverages Fuzzy Cognitive Maps (FCMs) to conduct comprehensive risk assessments, subsequently generating prioritized recommendations for predefined risk management measures aimed at preventing and/or reducing the most critical OSRs. The system's reliability has been validated by iterating the procedure with diverse input data (i.e., matrices of varying sizes) and measures. This confirms the system's effectiveness across a broad spectrum of engineering scenarios.

Keywords: recommendation system; networks and applications; uncertainty modeling

Citation: Carpitella, S.; Brentan, B.; Certa, A.; Izquierdo, J. A Recommendation System Supporting the Implementation of Sustainable Risk Management Measures in Airport Operations. *Algorithms* **2023**, *16*, 511. https://doi.org/10.3390/a16110511

Academic Editors: Frank Werner, Alicia Cordero and Juan Ramón Torregrosa Sánchez

Received: 2 October 2023
Revised: 30 October 2023
Accepted: 6 November 2023
Published: 7 November 2023

1. Introduction

Achieving sustainable airport operations requires a careful equilibrium between economic, environmental, and social aspects of sustainability, as highlighted in previous research [1]. Simultaneously, it is imperative to factor in the health and safety of workers who face various physical and psychological hazards, including noise, vibration, air pollution, and stress. This endeavor requires active collaboration among all stakeholders, such as airport operators, airlines, passengers, local communities, and government agencies. Collaborative efforts and partnerships among these stakeholders can uncover and implement innovative, effective solutions that advance sustainability goals [2], protecting the environment and public health. This requires a holistic approach that takes into account the complex relationships existing among sustainability factors and how they might affect occupational health. Sustainable airport operations offer numerous advantages, including enhanced air quality, reduced noise pollution, improved energy efficiency, and cost savings. These benefits contribute significantly to an airport's long-term success and competitiveness. The multifaceted nature of this challenge makes it an intriguing yet complex domain for human behavior engineering modeling. By comprehending how different sustainability factors intersect and influence human behavior, we can design interventions that endorse sustainable practices and safeguard workers' health. Hence, the development of suitable mathematical models for decision making becomes imperative when examining the mutual interplay of complex factors influencing sustainability and occupational health. These models enable a comprehensive evaluation of trade-offs among various dimensions of sustainability, equipping decision makers with a powerful instrument to enhance outcomes and steer policy formulation and implementation. The knowledge derived from these models is important in pursuing sustainable airport operations and economic growth by progressively achieving social and environmental sustainability objectives. These efforts are undertaken with a primary commitment to safeguarding the well being and safety of airport workers, thereby embracing a holistic approach to aviation excellence that transcends economic, social, and environmental dimensions.

The objective of this paper is to introduce a recommendation system designed to facilitate the implementation of risk management measures within airport operations. Our approach involves the development of a flexible recommendation system, which was programmed in Python and can be integrated into the airport, analyzed in our case study but also within other various operational contexts. The present research does not aim to introduce a novel methodological approach, but rather, to establish a comprehensive framework rooted in a well-established method within the academic literature whose recommendation and visualization features are herein automated and upgraded. This framework is designed to be readily understandable and applicable within corporate settings. To the authors' best knowledge, this marks the first application of this method within the specific domain of airport infrastructure, addressing the challenge of occupational risk management measures' implementation. This work is a substantial extension of a previous conference contribution [3], in which we analyzed a set of twelve relevant Occupational Stress Risks (OSRs) that can likely be experienced by airport workers. We developed a Fuzzy Cognitive Map (FCM) to address the inherent uncertainties and inner interconnections within the network of identified OSRs. This approach enabled us to formulate a targeted set of measures, primarily concentrated on enhancing both occupational and sustainability aspects, drawing from the most prominent risks identified via the FCM analysis. In the present paper, we pursue the following intermediate objectives.

- We first analyze, in a more comprehensive way, the identified OSRs by formalizing a set of targeted measures for all the OSRs and not only for the most interconnected ones, as previously performed in [3]. These measures are reported in the first table in Section 4.1 and referenced with the existing literature. This makes our approach flexible and less sensitive to variations in the input data that human experts elicit. Measures are specifically conceived to reduce the occupational stress of workers while optimizing sustainability aspects and could also serve as guidelines to be adopted in any airport scenario.
- We herein program a flexible recommendation system developed in Python language that is capable of printing indications in an automated way about the most suitable measures to be implemented with priority. We emphasize once again that the goal here is not of introducing a groundbreaking methodological approach. Instead, we strive to construct a holistic framework firmly grounded in a well-established method drawn from the academic literature and herein upgraded in terms of recommendation and visualization. This framework is designed to be easily understood and readily applicable within corporate environments. This may represent the pioneering implementation of this method in the specialized field of airport infrastructure, aimed at effectively suggesting management measures for reducing the complexities of occupational risk.
- We obtain the network of relationships by abandoning the MentalModeler software (https://www.mentalmodeler.com/, accessed on 1 October 2023) which we used in [3]. A significant limitation of the MentalModeler software for building FCMs is indeed its inability to provide a clear visual distinction for the most critical factors, which can impede the prioritization of key elements in the model. In this research, differently from the previous approach, we are now capable of automatically displaying the prioritization of OSRs in the network through different layers according to their greater impact. This solution was previously achieved by manually adjusting the network obtained via MentalModeler software.
- We validate the code by running it with different input data and, in particular, by using matrices elaborated in previous studies referring to different high-risk operational

contexts [4,5]. For each element of these new input matrices, we hypothesized a set of measures. We observe that, independently of the number of measures defined for each element, the system always recommends all the measures related to the most critical OSR(s). We enrich the validation section by using different matrices elaborated in the literature as the input for FCM in other sectors of activity and confirm results.

The recommendation system is ready to be used and applied in several scenarios and industrial contexts for optimizing the risk management process. The present paper is organized as follows. Section 2 covers the literature review, setting the theoretical foundation for the study. In Section 3, we define the methodological steps for implementing the system. Section 4 presents the application of our approach, introducing a case study at an Italian airport, discussing the results and validating the model with different input data. Lastly, in Section 5, we conclude the work by discussing both the advantages and limitations of the proposed approach and suggesting potential directions for future research.

2. Literature Review

2.1. Occupational WellBeing in High-Risk Environments

In high-risk work environments, such as aviation, emergency services, and construction, stress can significantly impact employee health and wellbeing [6,7]. Stress can undermine concentration and decision making [8], escalating the risk of accidents. Thus, the implementation of support measures is paramount for stress management and overall safety [9] in high-risk environments. As discussed in various works of research available in the literature, these measures range from comprehensive employee well-being programs focused on optimizing team resilience and work shifts [10], time management and stress management workshops [11], as well as access to periodic counseling sessions [12], to promoting a workplace culture based on open communication, work–life balance, and equitable workload distribution. Occupational stress encompasses physical, emotional, and psychological strain [13] resulting from multiple work-related factors. Abbasi et al. [14] evaluate the validity of eighteen empirical heat stress indices in predicting the physiological parameters of workers under varying occupational and environmental conditions. The results reveal the need for new indices tailored to specific conditions, highlighting the multifaceted nature of occupational stress, which can arise from factors like heavy workloads, tight deadlines, limited control, interpersonal conflicts, and job insecurity. Extended exposure to these stressors can result in severe repercussions, impacting mental and physical wellbeing, job performance, and overall quality of workers' lives. Mendes et al. [15] present a systematic literature review on risk management technological advancements, particularly emphasizing proactive, interactive, and predictive measures used for risk mitigation in the aviation sector. The study complements the concept that prolonged exposure to stressors can profoundly affect the wellbeing, performance, and overall quality of life of workers. The authors discuss that by embracing predictive and interactive methodologies, the quality and safety of systems can be enhanced by incorporating valuable feedback mechanisms. As demonstrated in our forthcoming case study, in such high-risk sectors as aviation, the imperative to address occupational stress is amplified, given its potential to escalate safety risks. With this special regard, King et al. [16] lead a two-part study involving creating and testing a new aviation safety display called Ecological Interface Design (EID). The authors demonstrate that, compared to traditional displays used by major aviation companies, EID presents user-friendly features that are significant for reducing the workload without affecting decision accuracy or situation awareness, showcasing the potential of EID to improve safety in aviation, especially in high-stress situations. Organizations must systematically evaluate occupational stress risks and develop effective management measures, as embracing a proactive approach to risk management ensures safety while generating a healthier and more secure workplace for employees. For example, De Almeida Oliveira et al. [17] explore the impact of physical exercises conducted within the workplace on reducing occupational stress among workers. The authors state that, in a world where technological advancements often take precedence over employee wellbeing, it is vital to address stress issues proactively. They develop a review, which includes seven articles, suggesting that workplace physical exercises may indeed have a positive effect on reducing occupational stress. However, they also acknowledge the need for further research to provide a clearer understanding of this potential. Leka et al. [18] analyze the relationship between key Occupational Safety and Health (OSH) policy principles, organizational responses to work-related stress, and employee experiences in Italy. Their study underscores the significance of OSH principles and the organizational culture underpinning them, demonstrating their positive impact on addressing work-related stress. However, it also highlights the importance of further support for organizations in developing primary prevention interventions at the organizational level specifically aimed at reducing job demands to create a safer and healthier work environment for employees. Ortiz-Barrios et al. [19] address the significant challenge of an aging workforce. The study provides a comprehensive approach for effectively managing the convergence of Occupational Safety & Health Performance (OSHP) and Industry Systems Productivity (ISP) in the context of an aging workforce, highlighting such factors as efficiency, quality, and psychosocial risk play an important part in jointly managing OSHP and ISP in this context. Broadly speaking, risk management approaches should help to understand and address health hazards in both existing and new operative environments while also providing valuable insights for shaping future regulatory and preventive strategies [20]. In this context, mathematical modeling plays a pivotal role, enabling enhanced safety measures and accounting for uncertain conditions.

2.2. Existing Modeling Approaches

Mathematical models enable the simulation and prediction of multiple scenarios and stressors in diverse, complex fields [21]. By meticulously quantifying stress factors, potential failures, and their consequences, these models empower decision makers to proactively identify vulnerabilities and allocate safety investments more effectively [22]. Additionally, mathematical modeling excels in handling unpredictability in high-risk environments, enabling an assessment of the effects of varying conditions and unforeseen events [23]. Consequently, it aids in safeguarding lives and assets but, above all, fosters a proactive approach to risk mitigation for critical systems, making them resilient in the face of the unknown. The literature proposes many models and techniques capable of solving complex problems in the risk management domain while considering uncertainty. De Lima and Seuring [24] discuss Circular Supply Chains (CSCs) and their role in promoting material circularity. Their study emphasizes the lack of attention to risk and uncertainty management within CSCs, proposing a Delphi study with experts from various countries to identify risks. The outcome is to offer strategies like collaboration and circular product design to manage these risks while accounting for contingency factors impacting CSCs. Brocal et al. [25] develop a qualitative approach to managing emerging risks in industrial settings, focusing on uncertainty as a critical factor. The authors introduce a theoretical framework that integrates uncertainty, knowledge, and understanding by proposing a classification scheme for emerging risks. The approach is applied to case studies involving various emerging risks. Liu et al. [26] conduct a comprehensive review of research on Occupational Health and Safety Risk Assessment (OHSRA). The review aims to identify and evaluate models and approaches for assessing and prioritizing the risk of occupational hazards in the workplace. The study reviews 88 publications from 2002 to 2022, categorizing them into seven groups based on OHSRA models and analyzing their risk criteria, weighting methods, and assessment approaches. Additionally, it conducts a bibliometric analysis to identify research trends and hotspots in the field, providing a valuable resource for scholars and practitioners involved in OHSRA and offering insights into current developments and future research directions. Cazzagon et al. [27] focus on the occupational risk assessment of magnetic nanoparticles used in such critical processes as medical imaging by employing a software-based Decision Support System (DSS) following regulatory requirements and making use of hazard and exposure assessment models. The study performs probabilistic risk characterizations, highlighting the scenario that poses non-negligible risks to workers and establishing specific management measures. Sarkar et al. [28] introduce a new method for improving occupational accident prediction using machine learning. The developed approach tackles challenges like data uncertainty and unstructured information by combining rough set-based predictive and topic modeling. The method also incorporates an optimized machine learning model and rule reliability assessment while leading experiments on various datasets, including real-life occupational safety data. Seah et al. [29] address the fatigue problem in aviation, highlighting the lack of a standardized protocol for assessing and managing it across the industry. The authors present a framework supported by real-world data and various measurements to monitor aircrew fatigue and performance to determine safe crew configurations for commercial airline operations. The study confirms the feasibility of this framework and its ability to provide valuable insights into fatigue and work performance, facilitating the development of safety recommendations. Gravel et al. [30] investigate occupational health and safety practices in the Canadian electronic waste recycling (e-recycling) industry, a type of high-risk environment where workers face exposure to toxic metals. Health risks for workers are estimated from multiple directions, and the use of protective equipment has been considered inadequate in most facilities. The study highlights the importance of sustainable risk management and collective control methods to optimize worker health and safety.

2.3. Research Gap

As it emerges, there is a consensus in the literature emphasizing the crucial need for developing flexible programs in occupational risk management, which should be adaptable to various workplace settings and conditions. To effectively manage occupational risks emerging in complex environments, the literature agrees on the importance of providing recommendations and clear indications to the company management about practical measures to be implemented. The flexibility of the adopted models, coupled with a proactive approach, ensures that organizations can better anticipate and mitigate emerging risks while safeguarding the health and wellbeing of their workforce.

In our research, we have identified a significant gap in the existing literature about the assessment and management of occupational risks, particularly in the context of their interdependence as well as in the collection of linguistic evaluations expressing the strength of their relations, integrating expert experience. Despite the wealth of models available for risk assessment, there is a notable scarcity of approaches that adequately address these critical aspects. With this regard, FCM is a powerful and well-recognized tool that has been underutilized in this domain. For example, the literature offers plenty of FCM-based applications connected with risk management in such fields as environmental engineering [31,32], healthcare [33], and policies and regulations [34], among others. This approach was also implemented and validated for risk analysis in airport contexts [35], but not with specific reference to occupational safety risks, our field of application.

We propose the integration of FCM in conjunction with developing a flexible recommendation system in a practical airport environment. Our approach also extends to developing improved visualization features by providing a final graph that displays elements in different layers according to their global significance. This cannot be automatically achieved via traditional visualization software, e.g., MentalModeler. To our knowledge, this practical approach has not been previously explored. By tailoring our contributions to the specific context of reference, we aim to provide valuable insights and tools that can significantly enhance the capabilities of practitioners, ultimately improving the context and content of their work in the realm of occupational risk assessment and management.

3. Methodological Approach

Our recommendation system was programmed in Python and advances the application of FCM as a valuable tool for comprehensively evaluating risks during the initial stages of planning or decision making. In essence, not only does this system assess risks, but it also goes a step further by generating well-ordered recommendations for prioritizing targeted risk management measures. This means that, apart from identifying potential issues, the system suggests practical solutions. Additionally, the recommendation system provides a user-friendly visualization of the results, making it easier for stakeholders to understand and act upon the findings. The robustness and dependability of this system have been validated by using diverse input data and, in particular, matrices of different sizes to ensure the robustness and reliability of the system under the variation in input evaluations and parameters. This automation empowers airports to efficiently address risk mitigation measures and enhance overall safety and operational efficiency. Significantly, this system is not limited to a specific type of airport or context, as it is adaptable and suitable for various functional scenarios and environments. Figure 1 synthesizes the proposed approach.

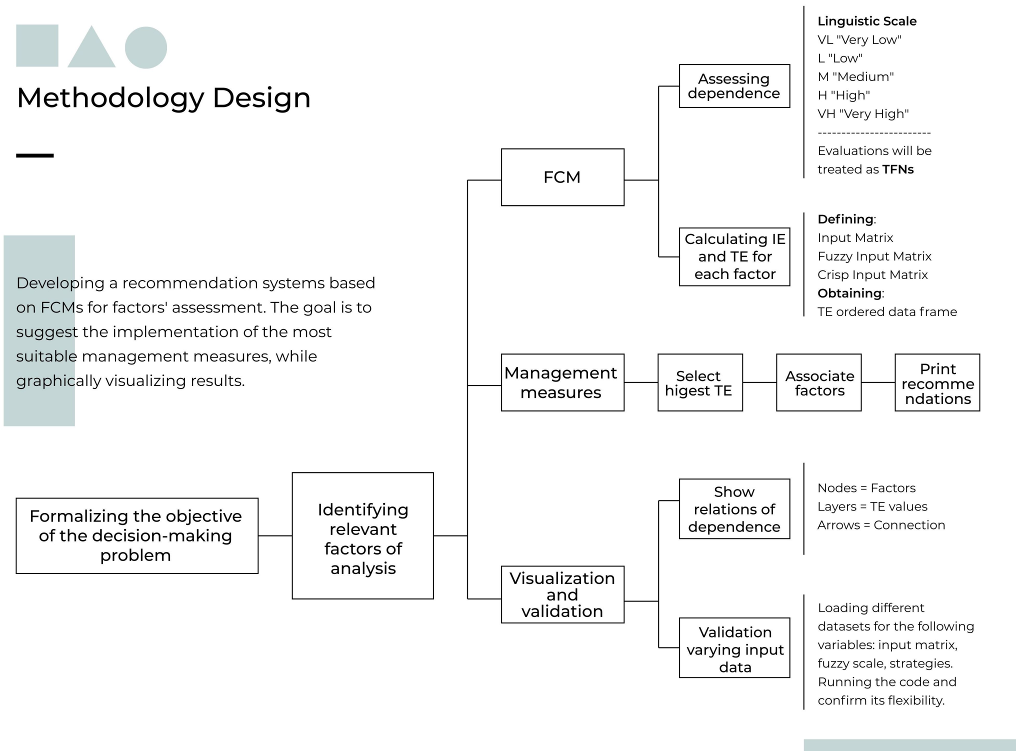

Figure 1. Methodological steps.

3.1. *Fuzzy Cognitive Map*

FCMs are mathematical models that represent relationships and interactions between various concepts or variables. These models use fuzzy logic, which help us to handle the inherent uncertainty in human decision making, offering several advantages. They assist in understanding the complex nature of the analyzed systems, providing insights into the contributing factors. By employing FCMs, we can make informed decisions, leading to the development of effective management measures. Specifically, FCMs offer several distinct advantages over other methodologies commonly used for risk assessment. Firstly, FCMs excel in capturing and representing complex, interconnected relationships among various risk factors and variables, making them well suited for modeling the complex nature of real-world systems, especially for cases lacking in statistical data [36]. This inherent capacity for modeling interdependencies sets FCMs apart from linear or deterministic models. Additionally, FCMs can incorporate expert knowledge and qualitative data, assisting managers and companies in attaining organizational goals by pinpointing control points and root causes, guiding risk management, and facilitating effective communication [37]. FCMs also ease the exploration of dynamic scenarios and "what-if" analyses, providing decision makers with a powerful tool for assessing the impact of various interventions and policy changes [38]. Furthermore, their advantages of strong interpretability, logical reasoning capability, and intuitive knowledge representation [39] allow for adapting FCMs to various domains, making them a versatile choice for risk assessment in diverse fields. As previously observed, FCMs can be beneficial in the field of occupational stress risk evaluation in assessing risk interdependencies. FCMs allow us to evaluate how different stress risks interact and influence one another, providing a comprehensive understanding of how these risks are interconnected within an occupational setting. Another useful issue can be predicting stress outcomes, as FCMs can simulate various scenarios and predict how interventions or changes in stress risk factors may impact occupational stress outcomes. This aids in the development of targeted measures for stress prevention and management. As reported by Nápoles et al. [40], a significant obstacle in constructing FCMs lies in maintaining the incorporation of human expertise while adapting the segments of the network that require learning from historical data. In our approach, we overcome this challenge by focusing on evaluating the interdependence of risks rather than relying on their specific values. Instead of assigning precise numerical values to risk factors, we assess the strength of their relationships within the FCM, allowing us to capture the qualitative aspects of risk interdependence while preserving human knowledge. By concentrating on the strengths of these relationships, we reduce the necessity to adjust parts of the FCM solely based on historical data, which can be limited and subject to change. This approach ensures that the FCM retains the insights and expertise of human contributors while incorporating the dynamic nature of risk interdependencies.

For more detailed FCM applications, please refer to [4,41,42].

3.2. Input Data and Recommendation

A squared input matrix collecting linguistic evaluations of influence between pairs of factors is defined according to the opinion provided by an expert in the field of the decision-making problem. Subsequently, these evaluations are translated to Trapezoidal Fuzzy Numbers (TFNs) in the format (a, b, c, d) and collected in the fuzzy input matrix. Each TFN within the fuzzy input matrix is systematically processed using a function defined as a replacement function, which is iterated to extract specific parameters (a, b, c, d) from the fuzzy scale and transform the TFNs into parameterized representations. This method returns the extracted fuzzy parameters corresponding to the linguistic evaluations of input (second table in Section 4.1), thus enabling a more precise characterization of each evaluation. Subsequently, the defuzzification process takes place via the definition of defuzzification. This function is iterated by computing the centroid of gravity of each TFN, as shown in [43,44]. The outcome of this operation is the derivation of crisp values, effectively replacing the initial TFNs. As an outcome, crisp values are collected in the crisp input matrix, representing the TFNs' defuzzified versions, wherein each entry embodies a crisp value rather than a TFN. This transformation enhances the data's interpretability and facilitates further analyses for the calculation, for each factor, of the related Indirect Effects (IE) and Total Effects (TE).

Factors with associated higher TE hold practical significance as they refer to a more significant influence or impact within the network. Decision makers often prioritize actions or interventions related to these influential factors, as they have the potential to yield more significant outcomes or changes within the system. The developed system performs a data analysis and recommendation process. It first ranks factors based on their TE values, calculated from the FCM application. Then, it associates specific management measures to each of the analyzed factors, simultaneously identifying the measures with the associated higher priority of implementation. Finally, it generates and prints out recommendations focusing on the measures related to the most crucial elements. This approach helps prioritize actions for safety improvement based on their impact.

3.3. Visualization and Validation

The final graph shows the intensity of the relation among factors by providing a clear visual representation of how the variables interact and influence each other within the FCM, aiding in understanding system behavior and relationships. Specifically, the system generates a directed graph where the nodes represent the main identified factors' variables and the edges show the strength and direction of the influence between them. This graphical representation helps illustrate how the risks interact and, in particular, which risk (or subset of risks) may likely impact the occurrence of other related risks. We will outline the methodological approach we developed to create the network. This network visualization technique aims to represent and highlight the connections and influence between elements within the input dataset. The key steps in this approach are explained.

- Node creation: an object is created to construct the network. We start by extracting factors' ID values from the dataset, representing the elements under consideration. These values serve as the nodes in the network.
- Edge formation: we iterate the procedure through the dataset and, for non-zero values, establish directed edges between nodes. Each edge's weight corresponds to the value of the dataset element, indicating the strength of the relationship. Notably, the edge with the maximum weight is identified, signifying its exceptional significance.
- Visualization layout: the layout for visualizing the network is developed, focusing on presenting nodes with higher TE values prominently. The procedure organizes nodes into layers based on their TE values, ensuring that nodes with equal TE values are grouped. This step results in a more intuitive and informative visualization.
- Network visualization: the network is plotted and the edges between nodes are drawn with varying attributes, such as width and color, depending on their weight. Edges with the highest weight (TE) are accentuated in a distinct color, making them easily distinguishable. The use of arrows indicates the direction of the influence in the network.
- Node labels: the network nodes are labeled with the same IDs as the factors they represent. These labels are placed on the nodes and formatted for clarity.
- Visual output: the procedure generates the final visualization, showcasing the network of relationships, with arrows indicating the direction of the influence, node labels displaying the element names, and varying edge attributes representing the strength of the relationships.

This methodological approach results in a visual representation of the relationships and influences within the dataset, allowing for a clear understanding of which elements have the most significant impact and how they relate to one another. It aids in identifying key elements and their interactions, which can be valuable for decision making and analysis. By updating input evaluations, the approach confirms its consistency in recommending predefined measures for the most interconnected elements. As previously specified, this flexibility allows the proposed method to be extended to any business sector and any decision-making problem focused on analyzing dependence within a dataset.

4. Case Study

4.1. Problem Setting

As stated before, airports can be highly stressful environments for operators, subjecting them to significant stress risks. An analysis of the frontline area of an Italian airport focuses on identifying and understanding a set of twelve main OSRs that may likely affect frontline workers. To gain deeper insights into the complex relationships linking these OSRs, an FCM was built on the set of the main stressful elements identified in the literature. These elements are summarized in Table 1, along with their citations and potential risk management measures. The described measures have been elaborated for each OSR during a brainstorming session led by the responsible for the safety and security system of the airport, who also contributed to providing the linguistic evaluations supplied in the input matrix (Table 2).

Table 1. OSRs and related management measures.

OSR	Measure
OSR1. High workload and demanding schedules leading to increased stress levels [45].	• M1.1. Workload management: implement efficient workload distribution and scheduling practices to prevent excessive work pressure on employees. • M1.2. Task automation: automate repetitive tasks to reduce employee burden and enhance efficiency.
OSR2. Tight deadlines and time pressure to ensure efficient operations [46].	• M2.1. Flexible scheduling: implement flexible work schedules to alleviate time pressure and allow for better task management. • M2.2. Priority-based task allocation: prioritize tasks based on urgency and importance to reduce unnecessary time pressure. • M2.3. Resource optimization: invest in efficient resource allocation and technology to streamline operations and meet deadlines without excessive pressure on employees.
OSR3. Balancing multiple tasks simultaneously, causing work overload and time constraints [47].	• M3.1. Task prioritization: establish clear priorities to ensure essential activities are addressed first, reducing time pressure. • M3.2. Workflow streamlining: implement efficient automation to handle multiple tasks seamlessly and reduce work overload.
OSR4. Dealing with difficult or upset passengers, leading to emotional stress [48].	• M4.1. Conflict resolution training: provide airport staff with training in conflict resolution and customer service skills to better handle difficult passengers. • M4.2. Support resources: establish support mechanisms or counseling services to help employees cope with the emotional toll of dealing with upset passengers. • M4.3. Clear protocols: develop protocols for handling challenging passenger situations, ensuring employees know how to respond effectively and reducing stress.
OSR5. Managing conflicts and resolving disputes between passengers [48].	• M5.1. Communication guidelines: develop clear communication guidelines for staff to de-escalate conflicts and resolve disputes peacefully. • M5.2. Conflict mediation training: provide staff with training to handle passenger disputes more effectively. • M5.3. Designated mediation points: create designated areas within the airport for conflict resolution staffed by trained mediators. • M5.4. Surveillance and security: enhance surveillance and security measures to deter and address potentially disruptive behavior, reducing conflicts.
OSR6. Maintaining friendly and professional conduct while handling complaints [48].	• M6.1. Feedback mechanisms: establish feedback channels for employees to report issues and seek guidance, reducing uncertainty-related stress. • M6.2. Supportive work environment: Foster a supportive workplace culture that encourages open communication and provides resources for stress management.
OSR7. Irregular and rotating shifts disrupting sleep patterns and causing fatigue [49].	• M7.1. Shift planning: implement predictable and stable shift schedules to minimize disruptions to sleep patterns. • M7.2. Regular health checkups: conduct regular health checkups to monitor and address sleep-related issues, ensuring employee wellbeing.
OSR8. Difficulty in maintaining work–life balance due to unpredictable schedules [50].	• M8.1. Advance scheduling notice: provide employees with advanced notice of schedules to allow for personal planning. • M8.2. Communication channels: encourage open communication between employees and management to address individual scheduling needs and concerns effectively.

Table 1. *Cont.*

OSR	Measure
OSR9. Social and personal life limitations resulting from working during weekends, holidays, or night shifts [51].	• M9.1. Flexible scheduling and shift rotation: allow employees to have a fair distribution of working hours, including weekdays and weekends off, reducing social and personal life limitations. • M9.2. Employee support programs: establish counseling services, stress management workshops, and resources to assist employees in coping with the challenges of working irregular hours. • M9.3. Job rotation and cross-training: rotate employees through different roles and responsibilities to break the monotony, prevent burnout, and enhance skills.
OSR10. High turnover rates due to insecurity hinder sustainable practices [52,53].	• M10.1. Enhance Job security measures: implement measures to enhance job security for airport employees, such as offering long-term contracts, providing clear career progression pathways, and ensuring fair and competitive compensation. • M10.2. Foster a positive organizational culture: prioritize employee wellbeing, open communication, and involvement in decision-making processes. • M10.3. Implement sustainable work practices: establish sustainable work practices within the airport environment, promoting work–life balance, reducing excessive workloads, and implementing stress management programs.
OSR11. Insufficient career development challenges airport sustainability [54].	• M11.1. Mentoring and skill enhancement: implement initiatives to engage employees and address their career development needs, aligning with airport sustainability objectives.
OSR12. Insecure employment undermines employee wellbeing and hinders airport sustainability [55].	• M12.1. Secure employment contracts: offer stable and secure employment contracts with fair compensation and clear career paths to enhance employee wellbeing and support airport sustainability. • M12.2. Employee engagement and empowerment: Foster a culture of employee engagement, involvement, and empowerment through decision-making opportunities, skill development, and recognition, promoting wellbeing and alignment with sustainability goals. • M12.3. Sustainable workforce practices: implement practices and provide resources for stress management, ensuring a healthy and sustainable workforce while addressing occupational stress risks.

Linguistic evaluations of input refer to the intensity of causality that an element imparts to another one, expressed as very low (VL), low (L), medium (M), high (H), and very high (VH). They have been respectively translated to the following TFNs, the same as used in [44], in the format (a,b,c,d): VL (0, 0.1, 0.2, 0.3); L (0.2, 0.3, 0.4, 0.5); M (0.4, 0.5, 0.6, 0.7); H (0.6, 0.7, 0.8, 0.9), and VH (0.8, 0.9, 1, 1), and collected in the fuzzy input matrix (herein not shown for the sake of space). The main diagonal is filled with zeroes as elements are not supposed to be connected with themselves. The TFNs have been consequently defuzzified by applying the centroid method, as explained in [43,44]. The related crisp input matrix is provided in Table 3.

We proceed by calculating values of IE and TE for each risk factor. An analysis is performed on the crisp input matrix (Table 3) involving the calculation of minimum values along its rows and columns. This computation is carried out to identify the smallest values in each row and column, excluding values marked as '0'. The results of these calculations are organized into suitable data frames featuring IE values for each risk factor, respectively calculated per row and column. Following this, we proceed by calculating TE values and determining the maximum value between IE per row and per column. The outcome is a new data frame, displayed in Table 4, which holds TE values for each risk factor ranked in descending order and the associated OSR and related measures.

Table 2. Input matrix collecting linguistic evaluations provided by the expert.

	OSR1	*OSR2*	*OSR3*	*OSR4*	*OSR5*	*OSR6*	*OSR7*	*OSR8*	*OSR9*	*OSR10*	*OSR11*	*OSR12*
OSR1	0	H	VH	H	H	H	VH	VH	VH	M	L	L
OSR2	VH	0	VH	H	H	M	VH	H	VH	M	L	L
OSR3	VH	VH	0	H	H	H	H	VH	VH	H	L	L
OSR4	H	H	VH	0	VH	VH	L	H	H	H	L	H
OSR5	H	H	H	VH	0	VH	M	H	M	M	M	H
OSR6	H	H	H	VH	VH	0	H	L	L	L	L	L
OSR7	M	M	M	VH	VH	VH	0	VH	VH	M	M	M
OSR8	VH	H	H	VH	VH	VH	M	0	VH	M	M	M
OSR9	H	H	H	H	H	VH	H	H	0	H	H	H
OSR10	H	H	H	H	H	H	H	H	H	0	VH	VH
OSR11	M	M	M	M	M	M	M	M	H	H	0	VH
OSR12	VH	VH	VH	H	H	VH	H	VH	VH	H	VH	0

Table 3. Crisp input matrix.

	OSR1	*OSR2*	*OSR3*	*OSR4*	*OSR5*	*OSR6*	*OSR7*	*OSR8*	*OSR9*	*OSR10*	*OSR11*	*OSR12*
OSR1	0.000	0.312	0.410	0.312	0.312	0.312	0.410	0.410	0.410	0.229	0.146	0.146
OSR2	0.410	0.000	0.410	0.312	0.312	0.229	0.410	0.312	0.410	0.229	0.146	0.146
OSR3	0.410	0.410	0.000	0.312	0.312	0.312	0.312	0.410	0.410	0.312	0.146	0.146
OSR4	0.312	0.312	0.410	0.000	0.410	0.410	0.146	0.312	0.312	0.312	0.146	0.312
OSR5	0.312	0.312	0.312	0.410	0.000	0.410	0.229	0.312	0.229	0.229	0.229	0.312
OSR6	0.312	0.312	0.312	0.410	0.410	0.000	0.312	0.146	0.146	0.146	0.146	0.146
OSR7	0.229	0.229	0.229	0.410	0.410	0.410	0.000	0.410	0.410	0.229	0.229	0.229
OSR8	0.410	0.312	0.312	0.410	0.410	0.410	0.229	0.000	0.410	0.229	0.229	0.229
OSR9	0.312	0.312	0.312	0.312	0.312	0.410	0.312	0.312	0.000	0.312	0.312	0.312
OSR10	0.312	0.312	0.312	0.312	0.312	0.312	0.312	0.312	0.312	0.000	0.410	0.410
OSR11	0.229	0.229	0.229	0.229	0.229	0.229	0.229	0.229	0.312	0.312	0.000	0.410
OSR12	0.410	0.410	0.410	0.312	0.312	0.410	0.312	0.410	0.410	0.312	0.410	0.000

Table 4. TE data frame, ranking OSRs and related measures.

Total Effect	**OSR Ranking**	**Strategies**			
0.31250	OSR9	M9.1	M9.2	M9.3	
0.31250	OSR10	M10.1	M10.2	M10.3	
0.31250	OSR12	M12.1	M12.2	M12.3	
0.22917	OSR1	M1.1	M1.2		
0.22917	OSR2	M2.1	M2.2	M2.3	
0.22917	OSR3	M3.1	M3.2		
0.22917	OSR4	M4.1	M4.2	M4.3	
0.22917	OSR5	M5.1	M5.2	M5.3	M5.4
0.22917	OSR6	M6.1	M6.2		
0.22917	OSR7	M7.1	M7.2	M7.3	
0.22917	OSR8	M8.1	M8.2		
0.22917	OSR11	M11.1			

The recommendation system has been designed to guide the implementation of measures associated with the OSR (or a subset of OSRs) that exhibit the highest TE value. Specifically, the system identifies and prioritizes risk factors with the highest TE value, indicating their significant impact on occupational safety. It focuses on the pertinent columns that contain relevant information, excluding those with missing data, to ensure that recommendations are comprehensive and actionable. Consequently, the system generates a concise and practical recommendation statement, advocating for the adoption of these prioritized measures to enhance safety (Figure 2). This statement serves as a clear and actionable guideline for safety improvement, as informed by the data analysis.

```
Console 1/A ×
It is recommended the implementation of the following measures to optimize safety:
M9.1, M9.2, M9.3
M10.1, M10.2, M10.3
M12.1, M12.2, M12.3
```

Figure 2. Final recommendation.

4.2. Visualization and Discussion of Results

The network of relations is represented in Figure 3.

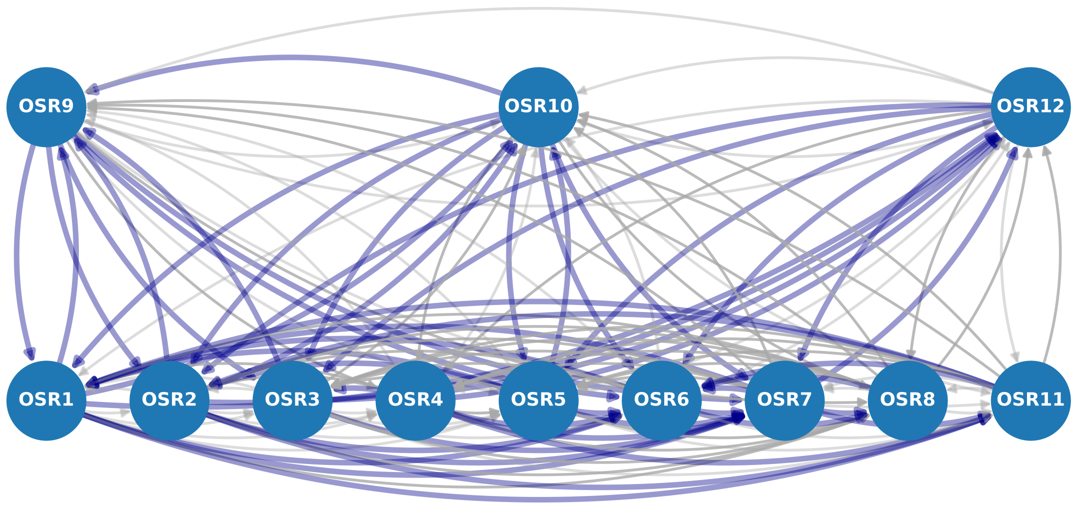

Figure 3. Network of relationships.

As it is possible to observe, the map was programmed to show as many layers as the values assumed by TE that are present in the TE data frame, which is two in our case, i.e., 0.3125 (associated with the linguistic evaluation "VH") and 0.229167 (associated to the linguistic evaluation "M"). This is another significant upgrade concerning paper [3] where, apart from leading calculations in a traditional way without implementing a comprehensive recommendation system, we generated the final network by using the MentalModeler software. While MentalModeler provides valuable insights, it has certain limitations that merit consideration. A significant limitation is its inability to automatically differentiate between distinct layers within the network, each representing various evaluations. This means that users are required to organize and adjust the network nodes manually to reflect these different evaluation layers. Additionally, the visualization generated by MentalModeler does not employ a color-coding approach to enhance clarity. On the contrary, our visualization approach uses a distinct color to highlight the arrows representing connections associated with the highest TE value. This color differentiation serves as a visual aid to draw attention to the most influential relationships within the network, making them easier to identify and interpret.

In reviewing the results, it becomes evident that occupational stress is a significant concern, particularly in workplaces characterized by high-risk dynamics. This stress can significantly affect both the wellbeing and performance of employees. Our comprehensive analysis, conducted using FCM, has endowed us with an in-depth understanding of the principal factors responsible for contributing to stress levels at the specific Italian airport object of this case study. This approach, rooted in the versatile FCM methodology, allows for insights into the complex nature of stress-inducing elements within the airport's operational framework. As it can be observed in Figure 3, the FCM analysis has revealed three critical occupational stressors of paramount concern:

- OSR9. Social and personal life limitations stemming from working during weekends, holidays, or night shifts

- OSR10. High turnover rates due to insecurity that obstruct sustainable practices
- OSR12. Insecure employment undermining employee wellbeing and hindering airport sustainability

Responding to these findings, our recommendation system automatically generates the set of related measures which had been previously formalized in Table 1 (refer to Figure 2) to be prioritized to mitigate these stressors and cultivate a more supportive and healthier work environment for airport employees. Our core objective is to improve employee wellbeing and performance by systematically addressing these challenges based on evidence. It is essential to note that the successful implementation of these recommended measures depends on the company and its available budgetary resources. While our analysis and recommendations offer a structured, evidence-backed approach to address occupational stressors, the company's commitment to allocate the necessary financial resources will be pivotal in ensuring the effective execution of these measures. Aligning budgetary allocations with these priorities empowers the company to take significant steps toward establishing a more productive and healthier workplace for its employees. Implementing the recommendations can reduce stress levels among airport employees, leading to improved wellbeing, job satisfaction, and overall performance, as outlined below.

- M9.1. Flexible scheduling and shift rotation: implementing flexible scheduling and shift rotation can help employees achieve a better work–life balance. This, in turn, can reduce stress levels, enhance job satisfaction, and decrease absenteeism, ultimately leading to improved productivity and employee retention.
- M9.2. Employee support programs: employee support programs, such as counseling services and mental health resources, can assist employees facing stress. These programs can improve mental wellbeing, reduce burnout, and create a more supportive work environment, improving overall job performance and satisfaction.
- M9.3. Job rotation and cross-training: These initiatives can reduce monotony and boredom in roles, prevent burnout, and enhance employees' skills and adaptability. This can result in increased job satisfaction, lower stress, and a more versatile workforce capable of handling various tasks efficiently.
- M10.1. Enhance job security measures: strengthening job security can alleviate employees' fears of job loss, reducing anxiety and stress. Job security measures can foster a sense of stability and commitment among employees, leading to increased loyalty and improved morale.
- M10.2. Foster a positive organizational culture: promoting a positive organizational culture that values open communication, teamwork, and employee wellbeing can create a more enjoyable and less stressful work environment. A positive culture can boost employee morale, motivation, and job satisfaction, ultimately improving performance and reducing stress-related issues.
- M10.3. Implement sustainable work practices: sustainable work practices, such as workload management and realistic goal setting, can prevent excessive stress due to overwork or unrealistic expectations. By implementing sustainable practices, employees can maintain a healthier work–life balance, resulting in reduced stress and enhanced job performance.
- M12.1. Secure employment contracts: secure employment contracts provide employees with a sense of stability and assurance, reducing the stress associated with job insecurity. Employees with secure contracts may experience less anxiety about their future, leading to increased focus on their current roles and improved performance.
- M12.2. Employee engagement and empowerment: engaging and empowering employees in decision making can boost their motivation and job satisfaction. Empowered employees are more likely to feel valued and committed, leading to reduced stress and higher performance levels.
- M12.3. Sustainable workforce practices: implementing sustainable workforce practices, such as a reasonable workload distribution and adequate rest periods, can prevent

employee burnout and stress-related health issues. These practices can help maintain a resilient and efficient workforce, positively impacting the overall performance.

4.3. Validation

When assessing the code's functionality, it is necessary to look closely at the underlying algorithm. As widely explained throughout this paper, the system acts as a tool for processing and analyzing data, eventually leading to the generation of recommendations based on specific criteria. Built on the FCM framework, the proposed algorithm includes converting input data into fuzzy numbers, defuzzifying these numbers, calculating indirect and total effects, ranking elements according to their total effects, and ultimately prioritizing recommendations addressing those factors characterized by higher TE values. Furthermore, the code employs a network of relationships to enhance the traditional representation of results. The validation process has been led with a clear focus on examining the algorithm's logical and mathematical integrity, ensuring that it aligns with the intended analytical purpose. In practical terms, this means verifying its robustness across input matrices of diverse sizes, assessing its consistency in treating different datasets, and understanding how it responds to atypical scenarios and changes in the data. In the context of validation, defining suitable metrics tailored to the specific problem domain is essential, enabling us to measure the quality of recommendations effectively.

We now validate the procedure, showing graphical results obtained by changing the input matrix containing linguistic evaluations expressed by experts. As a first input matrix, we use a larger matrix containing risk factors coming from the case study developed in previous research [4]. To run the system, it will be simply necessary to update the input data. The results are confirmed to be the same as reported in [4]. Figure 4 shows the network produced for this matrix, where we can clearly distinguish five different layers, each associated with different TE values, in a decreasing way. The obtained network represents a substantial advancement concerning the one reported in [4]. We want to stress further as elements with the associated highest TE occupy the first layers and, in some cases, as shown in Figure 4, the intensity of blue arrows can be lower for these elements. This can occur because an element's TE considers not only its direct connections but also the indirect ones through other elements in the map. Therefore, an element might have a high TE due to a web of indirect influences, even if its connections with certain elements are relatively weak. Essentially, when we consider the combined effect of numerous elements that may be indirectly linked, it becomes evident that their collective influence can result in a substantial TE, even if the individual relationships between these elements seem relatively weaker or less influential on their own.

To further strengthen the validation of our recommendation system, we now proceed by iterating the procedure by using another input matrix available in the literature. In detail, we use data coming from a study led by Hosseini et al. [56], which pertains to the mining sector, a high-risk environment that is distinct from airport infrastructure. This is to further corroborate the flexibility of our approach in dealing with different operational contexts. The mining sector poses substantial occupational risks spanning from the potential for accidents, environmental concerns, and the remote, challenging locations where mining activities take place. In carrying out the validation procedure, we used input data (collected by the authors in Table 8 [5]) and weighted TE values using their proposed approach (see weights reported in Table 9 [5]). We observe that the results are identical in terms of prioritization and, in our graphical representation (Figure 5), factors are automatically organized through layers according to the similarity exhibited in the ranking of factors reported by the authors (see Table 9 [5]). Our solution confirms that all the analyzed factors significantly affect the decision system of mining strategies.

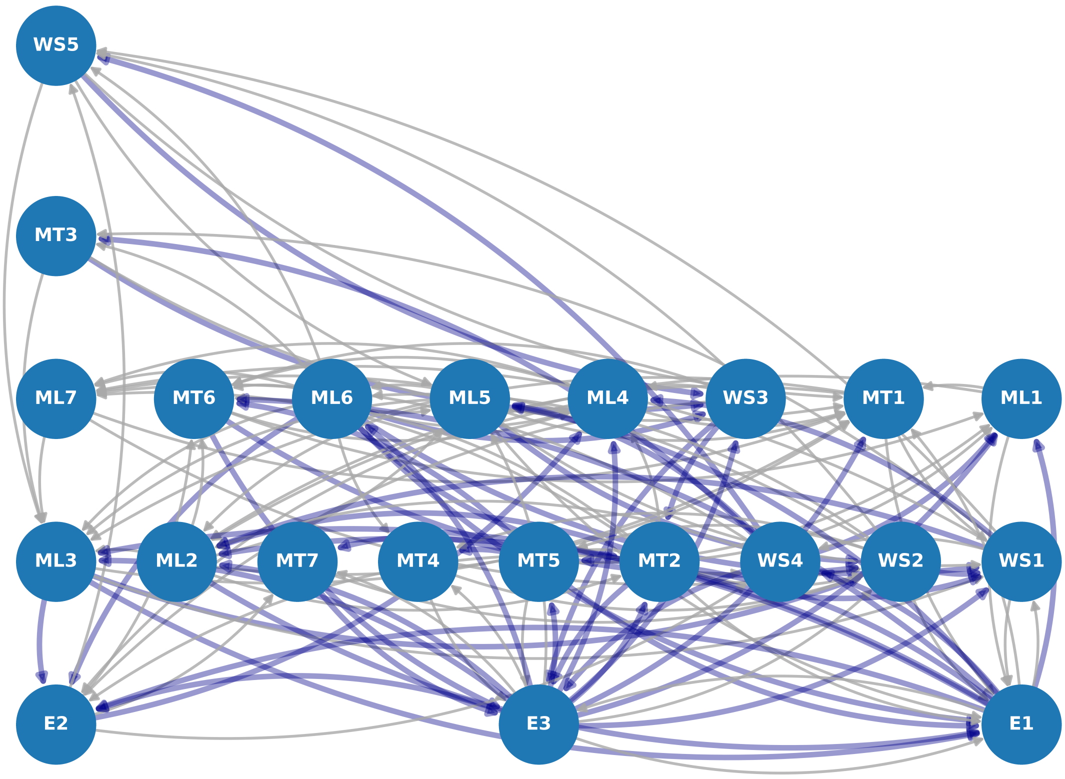

Figure 4. Network of relationship–validation [4].

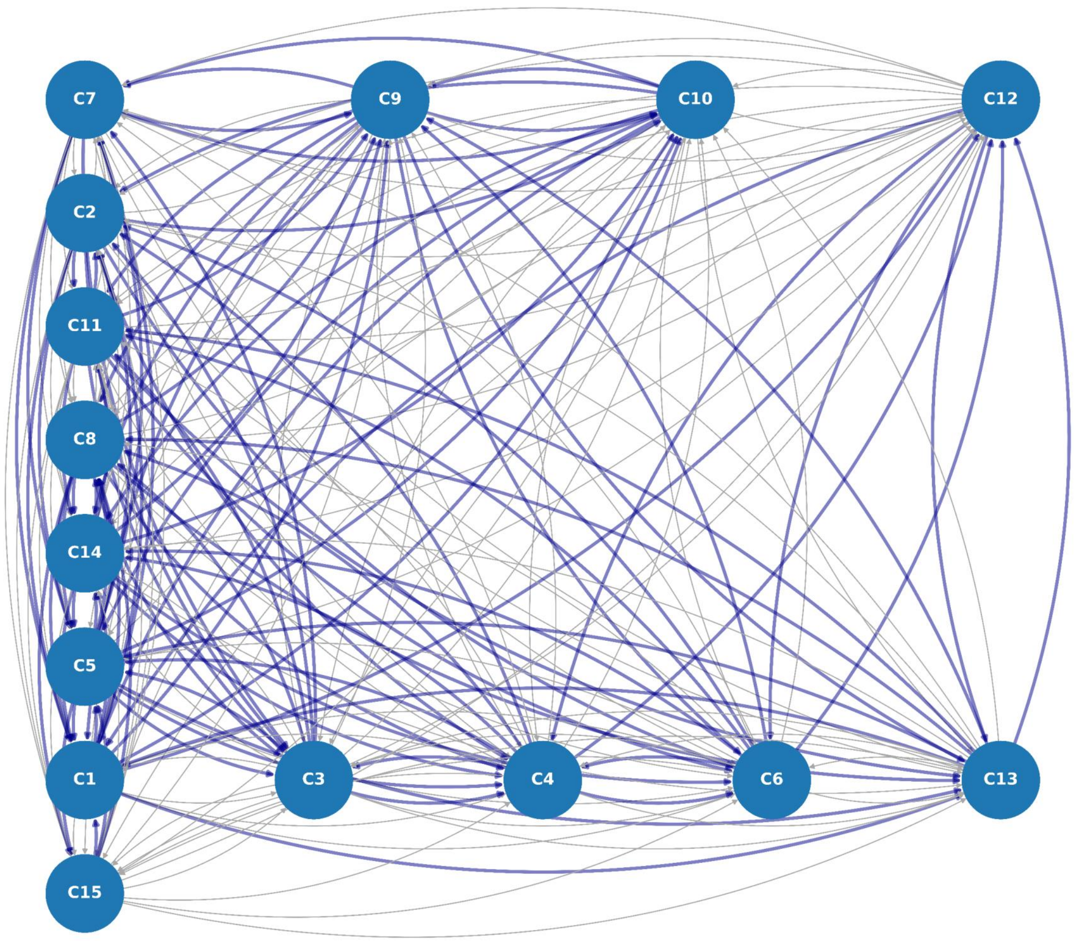

Figure 5. Network of relationship–validation [56].

5. Conclusions

This paper presents a recommendation system tailored to address sustainable risk management practices in airport operations, specifically focusing on identifying and evaluating stress-inducing factors categorized as OSRs, presented in Table 1. In close collaboration with airport management, a thorough analysis has been conducted for each identified OSR, resulting in a comprehensive set of measures aimed at stress reduction (Table 1). Implementing suitable measures enhances safety while promoting the wellbeing of employees who interact with the public. The recommendation system we have developed and validated can identify critical factors and propose priority measures for implementation, as shown in Table 4 and Figure 2. This system is highly flexible and adaptable, making it suitable for diverse operational sectors. We have embedded our recommendation system with a graphical representation technique that offers superior interpretative clarity compared to traditional models, as it is possible to appreciate in Figure 3.

The proposed recommendation system exhibits limitations, which we will address through future research. The major constraint lies in the prerequisite for a meticulously defined set of measures, which necessitates collaborative input from the company and is treated as an integral component of the input dataset. While we acknowledge the advantages of involving management in shaping this stage, future research could explore developing a more refined recommendation system capable of offering suggestions without mandating explicit input data. One potential approach could involve collaborative filtering, which relies on patterns and similarities within user–item interactions or behaviors, thereby preventing the need for exhaustive item attributes or predefined user preferences.

Author Contributions: Conceptualization, S.C.; methodology, software, and validation, B.B., S.C. and J.I.; formal analysis and investigation, B.B., S.C., A.C. and J.I.; resources and data curation, S.C.; writing—original draft preparation, S.C. and B.B.; writing—review and editing, A.C. and J.I.; visualization, S.C. and B.B.; supervision, J.I.; project administration, S.C. and J.I. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data can be available upon request.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CSCs	Circular Supply Chains
DSS	Decision Support System
EID	Ecological Interface Design
FCMs	Fuzzy Cognitive Maps
IE	Indirect Effect
ISP	Industry Systems Productivity
OHSRA	Occupational Health and Safety Risk Assessment
OSH	Occupational Safety and Health
OSHP	Occupational Safety & Health Performance
OSR	Occupational Stress Risk
TE	Total Effect
TFNs	Trapezoidal Fuzzy Numbers

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