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Evaluating advantages and disadvantages of twin avatar-based management: A multicriteria framework for assessing organizational impacts

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ABSTRACT

Digital technologies are reshaping managerial decision-making by enabling new forms of interaction, simulation and action in increasingly immersive virtual environments. Among these technologies, Twin Avatars (TAs) (*i.e.*, Artificial Intelligence (AI)-enabled digital representations of real individuals) are emerging as a potentially disruptive managerial tool with implications for organizational design, leadership and the future of work. By enabling enhanced digital presence, real-time interaction and scenario exploration, TAs can support faster and more adaptive decision-making in complex environments. Despite their growing relevance, research on the managerial implications of TA-based management remains limited. This study develops an analytic system to identify, structure and analyze key advantages and disadvantages associated with TA-based management. Adopting a constructivist perspective, the research combines the Nominal Group Technique (NGT) and DEcision MAking Trial and Evaluation Laboratory (DEMATEL) under a neutrosophic logic framework, allowing for the explicit treatment of uncertainty and causal interdependencies among relevant factors. The analytic system was developed through facilitated expert sessions and subsequently consolidated by an independent expert. The results identify influential advantages and disadvantages of TA-based management and reveal the perceived causal relationships among them. The study advances understanding of how agentic AI-enabled technologies may influence organizational decision-making and provides a structured basis for evaluating the organizational implications of TA-based management.

1. Introduction

Digital transformation has been driven by the rapid evolution of technologies such as Artificial Intelligence (AI), Virtual Reality (VR) and Augmented Reality (AR), which are reshaping business management practices (Aiolfi & Luceri, 2024; Mota et al., 2026). Among these technologies, AI has enabled new forms of immersive interaction, in which Twin Avatars (TAs) stand out as AI-enabled digital representations of real individuals operating in virtual environments. TAs not only appear and behave like humans but also facilitate communication, collaboration and decision-making (Kim et al., 2023; Silva & Campos, 2024).

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TAs enhance virtual interactions by fostering social presence and trust while contributing to organizational performance (Lind, 2025; Park et al., 2024; Zahedi et al., 2022). They have demonstrated value in communication, training, education and digital marketing, increasing brand trust, visibility and engagement (Silva & Campos, 2024). Accordingly, TAs are increasingly viewed as managerial tools capable of transforming communication, skill development and decision-making processes in digitally enabled organizations (Zahedi et al., 2022).

Despite growing interest in TAs, important gaps remain. First, existing studies largely emphasize technical development and isolated applications, with limited attention to strategic and managerial implications (Park et al., 2024; Silva & Campos, 2024). Second, the advantages and disadvantages of TA-based management remain insufficiently understood, particularly in decision-making contexts characterized by uncertainty (Chen et al., 2024; Kim et al., 2023). Third, research rarely examines the causal relationships among factors affecting TA adoption and performance, leaving organizations without structured guidance to anticipate impacts and trade-offs (Mota et al., 2026; Park et al., 2024). To address these gaps, this study poses the following research questions (RQs).

RQ1. What are the critical advantages and disadvantages of TA-based management?
RQ2. How can organizations evaluate the perceived causal relationships among these factors to support informed decision-making?

To answer these questions, the study employs a methodological combination that integrates Nominal Group Technique (NGT) and DEcision-MAking Trial and Evaluation Laboratory (DEMATEL) under a neutrosophic logic framework. This approach allows for the systematic structuring of criteria, capturing expert knowledge, professional experience and value judgments, while explicitly accounting for uncertainty, ambiguity and interdependencies among factors. By combining qualitative insights with quantitative modeling, the methodology provides a robust and realistic decision-support framework that is directly relevant to practitioners and managers navigating complex organizational environments.

The contribution of this study lies in developing and applying an analytic system that integrates NGT, DEMATEL and neutrosophic logic to evaluate the strategic implications of TA-based management. Importantly, this contribution should not be interpreted as the introduction of a novel methodology. Rather, it lies in applying this framework to TA-based management, positioning the phenomenon within the emerging discussion on agentic AI and developing distinct causal structures that reveal the perceived interdependencies among the advantages and among the disadvantages associated with TA adoption. Furthermore, although DEMATEL and neutrosophic logic have previously been combined in the literature, the specific methodological configuration adopted here differs from previous applications cited in this study, which relied on alternative problem-structuring methods (PSMs) rather than NGT.

Following this, the study contributes theoretically by advancing understanding of TA-based management, managerial decision-making under uncertainty and agentic AI. It identifies key advantages and disadvantages of TAs while modeling the perceived interdependencies among them. Practically, it provides an analytic framework to support the evaluation, prioritization and implementation of TA-based strategies. For policy-making and society, the study informs the responsible integration of emerging digital technologies, highlighting ethical considerations, human oversight and the preservation of uniquely human capabilities. Together, these contributions advance understanding of TAs as managerial tools and provide a coherent framework linking theoretical insights, managerial practice and societal implications. They also connect with emerging debates on agentic AI, organizational learning and human-technology collaboration.

The study is structured as follows. Section 2 provides a comprehensive review of the literature, highlighting key contributions and limitations in existing studies on TAs in organizational contexts. Section 3 details the research methodology and its constructivist underpinnings. Section 4 presents the empirical procedures and key findings derived from expert panel sessions. Finally, Section 5 concludes the study, discussing theoretical, practical and societal implications, and outlining directions for future research.

2. Literature review and research gaps

The concept of the "twin" originated at NASA in the 1970s, when mirrored spacecraft were used to simulate missions on Earth (cf. Lucchi, 2023). Michael Grieves formally introduced the term "Digital Twin" (DT) in 2003, defining it as a *"virtual representation of what has been produced"* (Grieves, 2014, p. 1). "[It] *refers to a digital replica of a physical entity, which can be a product, a system or a process"* (Chen et al., 2024, p. 104). Initially applied in manufacturing, DTs evolved from static, paper-based tracking to real-time sensing, using technologies such as lasers, vision systems and white-light scanning (Grieves, 2014). Today, DTs are central to smart manufacturing, enabling predictive modeling even during the production phase (Aziz et al., 2024).

Grieves (2014) identified three core components of a DT: (1) the physical product; (2) its virtual counterpart; and (3) a continuous data connection between the two. This interconnectivity relies on sensors, edge computing, AI, machine learning (ML), big data and communication technologies such as Internet of Things (IoT) and Bluetooth (Botín-Sanabria et al., 2022). Different types of DTs, including Digital Twin Instances (DTI), Digital Twin Prototypes (DTP) and Performance Digital Twins (PDT), support monitoring, simulation and optimization activities (Botín-Sanabria et al., 2022; Chen et al., 2024; Eumi, 2024). The maturity of DTs ranges from static representations to systems capable of supporting autonomous decision-making, reflecting increasing sophistication in integration and simulation capabilities (Botín-Sanabria et al., 2022).

DTs are supported by complementary technologies that enhance connectivity, intelligence and security. IoT enables real-time communication between physical and digital systems (Alonso et al., 2024; Attaran et al., 2024; Qays et al., 2023), while eXtended Reality (XR), including AR and VR, fosters immersive environments for simultaneous interaction with real and virtual elements (Rauschnabel et al., 2022). AI and ML facilitate reasoning, learning and autonomous decision-making (Burzykowski et al., 2023), big data supports the management of extensive datasets (Lu et al., 2019) and Cyber-Physical Systems ensure that real-world changes are accurately mirrored in digital environments (Cárdenas-Robledo et al., 2022). Blockchain further guarantees secure and transparent data storage through cryptographic verification (Jebri et al., 2024; Loporchio et al., 2023; Yang et al., 2024).

Despite this technological sophistication, research on DTs remains largely operational and manufacturing-focused, leaving strategic, managerial and organizational implications insufficiently explored. Importantly, DTs primarily seek to replicate, monitor and simulate physical assets, systems or processes through continuous data synchronization. Although they may incorporate AI-enabled functionalities, their central purpose is the representation and optimization of a physical counterpart rather than the emulation of human behavior or managerial decision-making (Attaran et al., 2024; Negri & Abdel-Aty, 2023). This distinction is particularly relevant when differentiating DTs from TAs, which are designed to represent and support human actors and their interactions within organizational contexts.

Recent advances in AI have enabled digital avatars capable of simulating aspects of human cognition, decision-making and emotional responses (Kohler et al., 2009; Park et al., 2024). These developments have also given rise to AI agents (*i.e.*, autonomous software entities that perceive information, reason and perform tasks on behalf of users or organizations). While AI agents may operate without visual

embodiment, TAs combine AI-driven capabilities with a digital representation intended to mirror a specific individual or organizational role.

The convergence of DT and AI-avatar technologies has contributed to the emergence of TAs as digitally embodied agents capable of supporting organizational processes and decision-making. TAs extend beyond operational efficiency to strategic applications, enabling scenario simulation, immersive engagement and human-like interactions across sectors such as marketing, tourism, training, recruitment and healthcare (Buhalis et al., 2023; Saeed et al., 2024; Silva & Campos, 2024). In marketing, TAs facilitate immersive branding and real-time customer feedback, while, in training, they simulate realistic environments to enhance skill development, engagement and knowledge retention. In remote work contexts, TAs restore social presence, strengthen team proximity and enhance collaborative decision-making, demonstrating their potential to shape the future of organizational management.

A complementary concept critical for understanding TAs is the Metaverse, introduced in Neal Stephenson's 1992 novel, which represents a virtual environment where people can interact in ways that closely mimic real-world experiences (Coelho et al., 2025). Through AR and VR, the Metaverse has become a key tool in engineering, management, training and organizational decision-making, enabling immersive environments that foster collaboration, learning and innovation (Negri & Abdel-Aty, 2023; Piccarozzi et al., 2024). Within these environments, users interact through avatars (*i.e.*, digital representations of themselves).

While the term *avatar* originates from Hinduism, signifying a deity's manifestation in human form, its digital interpretation has evolved from simple visual representations (Nowak, 2004) to highly realistic, human-controlled or AI-driven models that simulate behaviors, emotions and cognitive responses (Aiolfi & Luceri, 2024; Coelho et al., 2025). Avatars provide embodiment, allowing users to navigate virtual spaces, perform complex tasks, communicate non-verbally and engage in social interaction (Buhalis et al., 2023; Jebri et al., 2024). Research distinguishes between computer-controlled embodied agents and user-driven avatars, the latter of which reflect human behavior in immersive environments (Bailenson et al., 2004; Nowak & Fox, 2018; Piccarozzi et al., 2024).

To avoid conceptual ambiguity, this study adopts a clear distinction between DTs, AI agents, Metaverse avatars and TAs. DTs focus on representing physical entities, systems or processes. AI agents are autonomous computational entities capable of performing tasks and making recommendations. Metaverse avatars mainly provide digital embodiment and interaction within immersive virtual environments. TAs, in turn, integrate elements of these technologies by combining digital representation, AI-enabled capabilities, real-time interaction and decision-support functionalities (Buhalis et al., 2023; Negri & Abdel-Aty, 2023).

While the Metaverse provides the virtual environment and interaction space, TAs represent a broader and more versatile domain. Specifically, TAs are digital counterparts that can replicate, monitor and simulate human or organizational behaviors across multiple functions, extending beyond mere presence in immersive environments. In management contexts, TAs may support operational activities (*e.g.*, workflow optimization and process monitoring), human-resource functions (*e.g.*, personalized training, performance evaluation and skill development) and strategic planning (*e.g.*, scenario testing, risk assessment and collaborative decision-making) (Lind, 2025; Negri & Abdel-Aty, 2023). While Metaverse avatars primarily provide representation and interaction within virtual environments, TAs extend these capabilities, potentially incorporating real-world data, AI and modeling to support organizational decision-making and learning (Coelho et al., 2025; Piccarozzi et al., 2024). This versatility positions TAs not merely as representations within a virtual world, but as multifunctional decision-support tools capable of enhancing organizational efficiency, learning and innovation. Accordingly, the focus of the present study is specifically on TAs as AI-enabled digital representations that support managerial, operational and strategic activities within organizations, rather than on DTs, generic AI agents or conventional Metaverse avatars.

Despite these promising applications, the literature reveals significant limitations. Research is often fragmented, focusing on specific use cases without providing a comprehensive framework for managerial decision-making. Sample sizes tend to be small, interventions are short-term and studies are geographically or technologically constrained, limiting generalizability (Park et al., 2024; Yasuoka et al., 2022; Zahedi et al., 2022). While the advantages of TAs are described, the disadvantages, trade-offs and interdependencies remain underexplored (cf. Mota et al., 2026). Ethical and social considerations, including privacy, trust and user consent, are also frequently overlooked (cf. Coelho et al., 2025; Fehrenbacher & Weisner, 2024). Furthermore, few studies systematically examine the perceived causal relationships among factors influencing TA adoption, leaving managers without structured guidance for strategic implementation (cf. Park et al., 2024).

From a theoretical standpoint, these limitations also reflect the lack of a coherent lens through which the organizational implications of TAs can be understood. Existing research tends to emphasize technological functionalities and application domains, while paying comparatively less attention to the mechanisms through which TAs influence managerial processes, organizational learning and human-technology interactions. As AI-enabled technologies become increasingly capable of reasoning, adapting and supporting decisions, understanding their role within organizations requires moving beyond a purely technological perspective. In this regard, the emerging discussion on agentic AI offers a useful foundation for understanding TAs.

Unlike conventional digital tools, agentic AI systems are characterized by their ability to interact with users, process information, generate recommendations and participate in organizational processes in a semi-autonomous manner. Consistent with this view, TAs can be conceptualized not merely as digital representations but as AI-enabled organizational agents that mediate communication, facilitate knowledge exchange, support learning and influence decision-making activities. Their value therefore extends beyond operational efficiency and encompasses broader managerial and strategic implications.

This perspective also helps explain why the evaluation of TAs requires simultaneous consideration of technological, organizational, ethical and human dimensions. Benefits such as scalability, personalization and operational optimization coexist with concerns related to privacy, accountability, bias, creativity and human oversight. Consequently, understanding the causal relationships among these factors becomes essential for assessing the organizational consequences of TA adoption and implementation. These limitations highlight the urgent need for research that integrates technological, managerial and social perspectives to provide actionable insights for organizations navigating the adoption of TAs.

Building on these gaps, this study addresses two interrelated research questions: (RQ1) What are the critical advantages and disadvantages of TA-based management?; and (RQ2) How can organizations evaluate the perceived causal relationships among these factors to support informed decision-making? Addressing these questions requires a methodological approach that can capture expert knowledge, structure complex decision problems and model interdependencies under conditions of uncertainty. In response, the study adopts a constructivist methodological approach combining NGT and DEMATEL under a neutrosophic logic framework. This approach is expected to enable a systematic and rigorous evaluation of the advantages, disadvantages and perceived causal dynamics of TA-based management, while explicitly accounting for uncertainty, ambiguity and interdependencies among criteria. By adopting an agentic AI perspective, the study seeks to advance understanding of how AI-enabled digital representations can participate in organizational processes and shape managerial outcomes. In particular, it investigates how TAs may influence operational effectiveness, organizational learning, collaboration and decision-making under conditions of uncertainty.

Through this approach, the study offers a structured framework for

understanding TA-based management in organizational contexts, an area that remains largely underexplored in the academic literature. It seeks to clarify how TAs influence decision-making, operational efficiency and human-technology interactions, while advancing research on digital transformation, managerial decision-making under uncertainty and agentic AI. Specifically, the study contributes to the emerging literature on agentic AI by examining how digitally embodied agents may simultaneously generate organizational value, create managerial challenges and give rise to complex causal dynamics requiring systematic evaluation and oversight. By combining qualitative insights with quantitative modeling, the proposed analytical framework provides a rigorous and forward-looking approach for evaluating TA-based management, bridging gaps identified in the literature and laying the foundation for the research procedures and analytical techniques detailed in the following section.

3. Methodological background

This study adopts a constructivist methodological approach designed to integrate both objective and subjective elements into the analysis of TA-based management. The decision-support system was structured in three main phases: (1) problem structuring; (2) evaluation; and (3) recommendations (Belton & Stewart, 2002; Çipi et al., 2026). In the first phase, NGT was employed to gather, categorize and validate a comprehensive list of advantages and disadvantages associated with TA-based management. This technique enabled the structured incorporation of expert opinions, fostering consensus and minimizing cognitive bias. In the second phase, causal relationships among the identified advantages and among the identified disadvantages were analyzed using the DEMATEL method combined with neutrosophic logic, providing a robust interpretation of interdependencies while accounting for ambiguity and partial knowledge. The final phase involved system consolidation and interpretation of the influence-relation map to support practical recommendations.

3.1. Nominal Group Technique

NGT emerged in the 1960s within social psychology research and was designed to support effective group decision-making processes. It has since been applied across various domains, particularly in organizational and team contexts facing change (Delbecq & Van de Ven, 1971; Gil et al., 2026). According to Potter et al. (2004), its main applications include problem identification, solution development and priority setting. Oroszi (2020) notes that NGT is more structured than other techniques, minimizing group interaction to prevent dominant voices from overshadowing others and ensuring balanced participation.

The process follows a systematic sequence: (1) the facilitator introduces the decision problem and session goals; (2) individuals silently generate ideas independently; (3) ideas are listed and displayed publicly; (4) participants engage in a moderated, neutral discussion to clarify and evaluate suggestions; (5) each member anonymously ranks the ideas; and (6) a final round of silent voting produces a prioritized list. If consensus is not reached, the exercise is repeated. The session concludes with immediate feedback to participants (Potter et al., 2004). NGT supports both qualitative and quantitative analysis, making it a mixed-method tool (Gallagher et al., 1993; Çipi et al., 2026).

Key advantages of NGT include minimal preparation, short session duration (1 to 2 h), small group size (5 to 9 members), immediate feedback and reduced cognitive bias due to its high level of structure. It avoids premature decisions, fosters idea generation and promotes measurement of idea relevance (Potter et al., 2004). As Chen et al. (2021, p. 2) emphasize, it is *"a democratic method that initially increases the involvement of each group member and gives each member opportunities to express their own ideas, which expand the breadth of the topic"*. Additionally, *"individual brainstorming and the round-robin procedure remove the ideas from their creator, reducing a person's hurt when an idea is challenged"* (Bartunek & Murninghan, 1984, p. 429).

In the context of the present study, the adoption of NGT is particularly appropriate given the exploratory and multidimensional nature of TA-based management. The topic involves technological, organizational, ethical and human dimensions, which are often perceived differently depending on professional background and experience (Coelho et al., 2025). NGT provides a structured environment that ensures balanced participation and prevents hierarchical or dominant voices from disproportionately influencing the identification of advantages and disadvantages. This is especially relevant when discussing emerging technologies, where enthusiasm, skepticism and uncertainty may coexist. By combining individual reflection with moderated collective discussion and anonymous prioritization, NGT allowed the panel to generate a comprehensive and systematically ranked set of criteria grounded in practice. Consequently, the technique enhances the credibility, transparency and traceability of the criteria selection process, providing a robust foundation for the subsequent neutrosophic DEMATEL analysis.

3.2. Neutrosophic logic

One of the major challenges in AI-based contexts is managing uncertainty. Decision-makers aim to address cases that are neither entirely true nor entirely false (Mallik et al., 2022). To tackle this issue, Florentin Smarandache introduced neutrosophic logic in 1995, seeking to overcome the limitations of fuzzy logic, which does not explicitly account for indeterminacy (Al-Subhi et al., 2018). Because neutrosophic theory considers all aspects of decision-making (*i.e.*, agreement, disagreement and uncertainty), it has found wide application in complex decision-making environments (Al-Subhi et al., 2018; Gil et al., 2026).

Neutrosophic set theory addresses ambiguity and uncertainty by incorporating a third dimension beyond truth and falsity (*i.e.*, indeterminacy). This allows decision models to better handle missing or imprecise information (Abdel-Basset et al., 2019). As Gholami et al. (2022, p. 3) note, neutrosophic logic is *"described by three membership functions, namely truth-membership (T), falsity-membership (F) and indeterminacy-membership (I)"*. In a neutrosophic set S, each element is expressed as (T, I, F), where T%, I% and F% represent degrees of truth, indeterminacy and falsity, respectively. These values are considered real subsets of the interval]-0,1+[. According to the principle $0 \leq T + I + F \leq 3+$, the combined values may exceed 100%. This is due to the logic's capability to distinguish between relative truth (*i.e.*, truth in one or some worlds, denoted as "1") and absolute truth (*i.e.*, truth in all possible worlds, represented as "1+"). The same logic applies to relative falsity (denoted by "0") and absolute falsity (represented by "-0") (Ashbacher, 2002; Gokasar et al., 2023).

Neutrosophic logic enables a more refined evaluation of uncertain phenomena compared to binary or fuzzy approaches (cf. Ashbacher, 2002; Gholami et al., 2022; Vaz-Patto et al., 2024). By translating subjective expert assessments into quantifiable components of truth, indeterminacy and falsity, neutrosophic logic allows vague or incomplete data to be analyzed with mathematical rigor, particularly when paired with techniques such as DEMATEL for causal analysis and priority setting in ambiguous contexts (Abdel-Basset et al., 2019; Al-Subhi et al., 2018; Mallik et al., 2022).

For the empirical dimension of this study, neutrosophic logic is combined with the DEMATEL technique, which requires crispifying the values corresponding to the neutrosophic components of truth, indeterminacy and falsity (*i.e.*, aggregating T, I and F into a single value). To achieve this, the formula for crispifying neutrosophic values proposed by Pramanik et al. (2016) is employed. It is represented by $w_k = (T_k, I_k, F_k)$ and can be calculated as shown in Equation (1):

$$w_k = \frac{1 - \sqrt{\left((1 - T_k)^2 + (I_k)^2 + (F_k)^2\right)/3}}{\sum_{k=1}^{r}\left\{1 - \sqrt{\left((1 - T_k)^2 + (I_k)^2 + (F_k)^2\right)/3}\right\}} \quad (1)$$

In this formula, r refers to the total number of evaluations performed by the experts, and two assumptions must be followed: (1) $w_k \geq 0$ (*i.e.*, the neutrosophic values must be equal to or greater than zero); and (2) $\sum_{k=1}^{r} w_k = 1$ (*i.e.*, the sum of the crispified neutrosophic values of the ratings must total 1) (cf. Pramanik et al., 2016). For completeness, the single-value neutrosophic score function developed by Smarandache (2020), which represents an alternative approach available in the literature, is also presented in Equation (2):

$$s\,(T, I, F) = \frac{T + (1 - I) + (1 - F)}{3} = \frac{2 + T - I - F}{3} \quad (2)$$

The average positive quality function of a neutrosophic number classifies the T (*i.e.*, truth) component as a "positive quality", while the I (*i.e.*, indeterminacy) and F (*i.e.*, falsity) components are considered "negative qualities". Furthermore, $1-T$ is treated as a negative quality, whereas $1-I$ and $1-F$ are regarded as positive qualities (Smarandache, 2020). Both approaches allow the three neutrosophic components to be transformed into a single numerical value, thereby converting them into a single-component (*i.e.*, crisp) logic and facilitating the integration of neutrosophic logic with other methodologies. In practice, neutrosophic logic provides a flexible approach because, by explicitly considering indeterminacy, it can accommodate uncertain, imprecise and incomplete information in multicriteria decision-making contexts. According to Mallik et al. (2022) and Vaz-Patto et al. (2024), it provides a richer representation of real-world information by explicitly incorporating indeterminacy.

In the specific context of this study, the use of neutrosophic logic is justified by the inherent uncertainty and ambiguity surrounding TA-based management. The evaluation of advantages and disadvantages associated with emerging technologies rarely involves clear-cut judgments. Instead, experts may express partial confidence, hesitation or conflicting perceptions. By explicitly incorporating degrees of truth, indeterminacy and falsity, neutrosophic logic allows these nuances to be formally represented during the elicitation and aggregation of expert judgments rather than being reduced immediately to a single deterministic value. This is particularly relevant when dealing with ethical concerns, privacy risks, algorithmic bias and human–technology interaction, where expert perceptions may not be absolute (cf. Gokasar et al., 2023).

Accordingly, the contribution of the neutrosophic layer in the present study is primarily representational: it provides a formal mechanism for incorporating uncertainty into the expert-judgment process before the resulting assessments are transformed into crisp values for the subsequent DEMATEL analysis. The approach is therefore not intended to imply that neutrosophic DEMATEL necessarily produces different or superior rankings relative to conventional DEMATEL, but rather to provide a structured means of representing uncertainty and indeterminacy in the underlying expert assessments.

3.3. DEMATEL

The DEMATEL technique was developed in the 1970s (Gabus & Fontela, 1972), at the Geneva Research Centre of the Batelle Memorial Institute, to address and resolve complex, interconnected problems (cf. Si et al., 2018; Tzeng et al., 2007). Considered a method within the Multiple Criteria Decision Analysis (MCDA) domain, DEMATEL has been applied across various fields and enables the analysis of relationships among factors, visually representing these connections (Vaz-Patto et al., 2024; Zhou et al., 2017). Its ability to evaluate causal relationships among criteria makes it an effective tool for integrating expert knowledge and determining the relative importance of criteria based on their interactions (Gökler & Boran, 2025).

The method includes a visual representation, the Impact-Relation Map (IRM), which illustrates the causal relationships among decision-making criteria and allows for the identification of the most influential factors, which can then be prioritized in subsequent analyses. In this way, DEMATEL facilitates the analysis of causal dynamics among identified factors, supporting more informed and deliberate decision-making (Pinto et al., 2021). Fig. 1 presents the sequence of steps involved in a typical DEMATEL application.

Step 1 | In the first step, the opinions of a group of m experts are gathered to identify the degree of direct influence between each pair of factors, aiming to calculate the average matrix Z (Pinto et al., 2021). Among n factors defined by the experts, the degree of influence from factor i over factor j is represented by x_{ij}, expressed on a scale from 0 to 4, interpreted as follows: 0 = "no influence"; 1 = "low influence"; 2 = "medium influence"; 3 = "high influence"; and 4 = "very high influence". For each expert, an n x n matrix $X^k = \left[x_{ij}^k\right]$ is created, where k refers to the number of participating experts, with $1 \leq k \leq m$. The average matrix $Z = \left[x_{ij}\right]$, representing the mean influence values assigned by m experts, is obtained using Equation (3):

$$\mathcal{Z}_{ij} = \frac{1}{m}\sum_{i=1}^{m} x_{ij}^k \quad (3)$$

Step 2 | The second step involves creating a normalized direct-relation matrix D, so each matrix value lies between 0 and 1 (*i.e.*, $D = [d_{ij}]$) (Pinto et al., 2021). Equation (4) and *(5)* are used:

$$D = \lambda \text{ x } Z \quad (4)$$

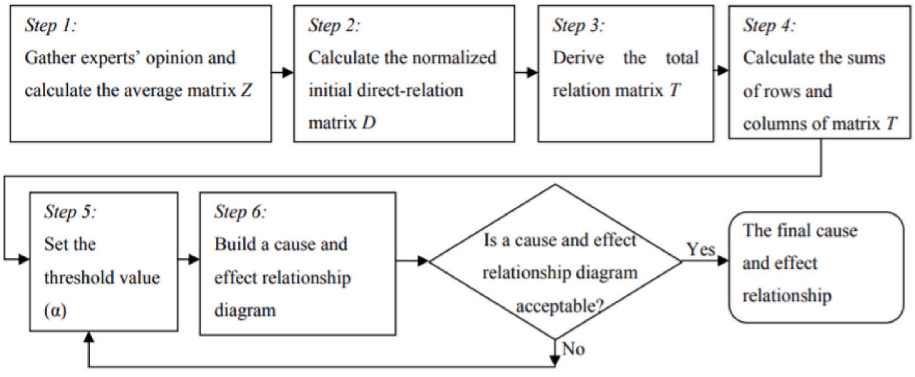


Fig. 1. Dematel processual steps.
Source: Sumrit and Anuntavoranich (2013).

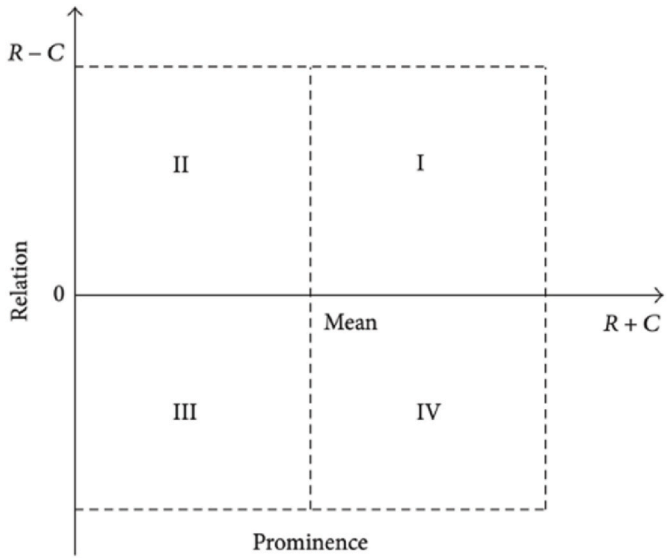


Fig. 2. Influence relation map.
Source: Si et al. (2018, p. 11).

$$\lambda = Min\left[\frac{1}{max\ 1 \le i \le n \sum_{j=1}^{n} |x_{ij}|}, \frac{1}{max\ 1 \le i \le n \sum_{i=1}^{n} |x_{ij}|}\right] \tag{5}$$

Step 3 | The third step derives from the total relation matrix T, where I is the identity matrix n x n and t_{ij} represents the indirect effect of factor i on j. Equation (6) results in the matrix T, showing the degree of influence in each pairwise relationship:

$$T = D\,(I - D)^{-1} \tag{6}$$

Step 4 | In this step, the total degrees of influence are calculated for the rows and columns of matrix T. Vectors r and c represent the row and column sums respectively, as shown in Equation (7) and *(8)*:

$$\mathrm{r} = \left[\sum_{j=1}^{n} t_{ij}\right]_{n\times 1} = [r_i]_{n\times 1} \tag{7}$$

$$c = \left[\sum_{i=1}^{n} t_{ij}\right]'_{1\times n} = [c_j]'_{1\times n} \tag{8}$$

r_i indicates the total direct and indirect effects received by criterion i. c_j denotes the total effects that criterion j has over others. The value $r_i + c_i$ reveals the total influence of factor i, while $r_i – c_i$ determines the cause-effect group (*i.e.*, if positive, the criterion is a cause (influencer); if negative, it is an effect (influenced)) (Khatun et al., 2023).
Step 5 | A threshold value (α) is set based on the average of all T matrix elements. This value is used to remove less significant criteria, simplifying rather than complicating decision-making (Pinto et al., 2021). Equation (9) defines α, with N as the total number of elements in T:

$$\alpha = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}[t_{ij}]}{N} \tag{9}$$

Step 6 | The final step is the construction of the DEMATEL diagram, mapping all coordinates ($r_i + c_i$; $r_i – c_i$) to visualize interrelationships and determine the most influential criteria (Pinto et al., 2021). As illustrated in Fig. 2, the diagram is divided into four quadrants. The first quadrant (QI) contains the core factors, which present strong relationships and greater prominence. The second quadrant (QII) includes driving factors, which have strong relationships, but less prominence. The third quadrant (QIII) gathers independent factors, showing both weak relationships and less prominence. The fourth quadrant (QIV) holds impact factors, with weak relationships, but greater prominence. The values R + C and R–C define the horizontal and vertical axes, respectively (Taherdoost & Madanchian, 2023).

Although the final rankings are not determined solely by the direct evaluations in matrix Z, criteria receiving systematically high assessments may be expected to occupy prominent positions, particularly when those influences are reinforced through indirect relationships captured in matrix T. The interpretation of DEMATEL outputs should therefore consider both the original expert judgments and the network structure generated through the propagation of influences.

As with any method, DEMATEL has both strengths and limitations. According to Taherdoost and Madanchian (2023), the technique enables the analysis of direct and indirect influences, clarifies complex causal relationships and visualizes them through the IRM. It highlights mutually influential factors, identifies key evaluation criteria, allows rational weighting based on interdependence and integrates expert input for both qualitative and quantitative criteria (Pinto et al., 2021). However, it does not account for additional criteria beyond those evaluated, nor does it correct for individual expert bias in assigned weights (Taherdoost & Madanchian, 2023).

In the context of TA-based management, analyzing relevant criteria and factors can significantly enhance decision-making, helping to address challenges such as technological integration and resource constraints. NGT supports the identification of key advantages and disadvantages by consolidating expert input, while DEMATEL maps perceived causal relationships and identifies the most influential factors. Neutrosophic logic complements these methods by effectively handling uncertainty and subjectivity in expert assessments. Together, these methodologies provide a structured foundation for investigating the advantages, disadvantages and causal dynamics associated with TA-based management, thereby supporting informed decision-making and organizational learning.

4. Application and results

A panel of experts was formed to identify the relevant criteria for analyzing TA-based management. According to Potter et al. (2004), the ideal size for a decision-making group is between five and nine participants. Accordingly, a panel of five experts was assembled, selected based on the following criteria: (1) knowledge and experience in AI, with a particular focus on TA technology; (2) a multidisciplinary perspective, reflected in diverse academic backgrounds and professional sectors; and (3) availability and willingness to participate in the study sessions. While all panel members were located in Portugal, they possessed substantial international experience through their involvement in multiple European projects relevant to the study. Consequently, participant selection was guided by the relevance of expertise rather than geographical representativeness.

This approach is consistent with the constructivist and process-oriented foundations of the study, where the objective is not to achieve statistical representativeness but to engage participants capable of contributing informed judgments, diverse perspectives and context-specific knowledge. As noted by Ackermann (2012), Belton and Stewart (2002), Bell and Morse (2013) and Ormerod (2020), the value of such interventions derives from the quality of stakeholder contributions, the diversity of viewpoints considered and the depth of dialogue generated, rather than from statistical inference. The composition of the panel therefore aligns with the logic underpinning PSMs, which emphasize meaningful knowledge elicitation and collective learning in

Table 1
Identification of advantages resulting from the first session.

Advantages (V)	
V1	Use in routine tasks
V2	Operational management
V3	Educational and didactic aspects
V4	Personalized experience for training and development
V5	Repeatability and reproducibility
V6	Time saving and full availability
V7	Monitoring and improvement of work processes
V8	Scalability in knowledge and decision-making
V9	High personalization capacity

Table 2
Identification of disadvantages resulting from the first session.

Disadvantages (D)	
D1	Personal data
D2	Privacy
D3	Loss of creative freedom
D4	Mechanization and lack of sensitivity in decision-making and analysis
D5	Lack of accountability
D6	Risks to mental health
D7	Security problems
D8	Bias
D9	Associated costs
D10	Difficulty in people management

complex decision-problem situations. Given the geographic dispersion of the experts, the sessions were conducted online, enabling efficient collaboration and interaction across locations.

4.1. Structuring phase: Nominal Group Technique

The first session focused on the structuring phase, whose primary purpose was to identify the advantages (V) and disadvantages (D) associated with TA-based management. The session lasted approximately 1 h and began with a brief presentation by each participant, followed by an overview of the topic and methodology. To stimulate reflection, the following trigger question was posed: *"Considering your values and professional experience, what advantages do you find in TA-based management?"*. Participants first reflected individually on the question before sharing their ideas in a structured manner, without interruptions or discussion at this stage, ensuring equal opportunity for expression. After all ideas were presented, a group discussion ensued to clarify, refine or eliminate ideas/criteria until consensus was reached. This process resulted in the identification of nine advantage criteria: (V1) *Use in routine tasks*; (V2) *Operational management*; (V3) *Educational and didactic aspects*; (V4) *Personalized experience for training and development*; (V5) *Repeatability and reproducibility*; (V6) *Time saving and full availability*; (V7) *Monitoring and improvement of work processes*; (V8) *Scalability in knowledge and decision-making*; and (V9) *High personalization capacity*.

To examine potential drawbacks, the session continued with the second trigger question: *"Considering your values and professional experience, what disadvantages do you find in TA-based management?"*. Following the same procedure, the experts identified and discussed the main barriers to adopting the TA technology. After analysis and consolidation, ten disadvantage criteria were established: (D1) *Personal data*; (D2) *Privacy*; (D3) *Loss of creative freedom*; (D4) *Mechanization and lack of sensitivity in decision-making and analysis*; (D5) *Lack of accountability*; (D6) *Risks to mental health*; (D7) *Security problems*; (D8) *Bias*; (D9) *Associated costs*; and (D10) *Difficulty in people management*.

The criteria identified during the first session enabled the construction of Table 1andTable 2, giving participants a clearer and more structured view of the aspects highlighted by the group across both dimensions analyzed in the study.

Table 1andTable 2 clearly and systematically capture the contributions of the experts involved in the first group work session, reflecting their experience and domain knowledge. The use of NGT was particularly important in this phase, as it ensured equal participation, reduced the influence of dominant voices and promoted independent idea generation before collective discussion. This structured process allowed a wide range of perspectives to emerge, covering not only technological and operational aspects but also managerial, ethical and human-centered considerations related to TA-based management.

Although the process is inherently characterized by a degree of subjectivity, the iterative discussion and consolidation stages played a critical role in refining and consolidating individual inputs into a shared and more mature understanding of the topic (cf. Gil et al., 2026). Through clarification, comparison and negotiation of viewpoints, initially fragmented or overlapping ideas were reinterpreted, merged or discarded, resulting in a coherent and collectively endorsed set of advantages and disadvantages. Consequently, the criteria presented in Table 1andTable 2 go beyond a simple aggregation of opinions and instead represent a negotiated and enriched representation of expert knowledge regarding TA-based management, providing a solid foundation for the subsequent causal analysis conducted using DEMATEL and neutrosophic logic.

4.2. Evaluation phase: Neutrosophic logic and DEMATEL

Following the structuring phase, in which the relevant criteria for the analytic system were identified based on the experts' contributions, the evaluation stage was carried out, which forms the basis of the application of the DEMATEL method in a neutrosophic framework. This phase corresponds to the quantitative approach of the study. To this end, two more work sessions were held, each lasting approximately 1 h, in a remote environment. The focus of these sessions was the construction of two influence matrices representing the criteria identified during the structuring phase. These matrices enabled the analysis of the perceived interdependence and causal relationships among the different factors.

At the beginning of each session, a brief presentation of the DEMATEL technique and neutrosophic logic was given, ensuring that participants understood the methodological procedures. Experts were asked to assign levels of influence among the criteria based on the DEMATEL scale from 0 to 4 (*i.e.*, 0 = "no influence"; 1 = "low influence"; 2 = "medium influence"; 3 = "high influence"; and 4 = "very high influence"). At the same time, participants indicated the confidence associated with this assessment, according to the three neutrosophic components: (1) degree of truth (*T*%); (2) degree of indeterminacy (*I*%); and (3) degree of falsity (*F*%). As explained in Section 3, it is important to note that the sum of the neutrosophic values does not need to total 100%, giving greater reliability and authenticity to the experts' perceptions (Gil et al., 2026). Based on the criteria outlined in the first session (see Table 1), the neutrosophic evaluations were collected and consolidated in the matrix *Z* presented in Table 3. This matrix reflects the levels of influence between criteria related to the advantages of TA-based management, as collectively assessed by the expert panel.

Table 3 corresponds to the aggregated direct-relation matrix *Z* obtained through discussion and negotiation among the panel members. In line with the neutrosophic approach adopted in this study, the matrix is presented in its neutrosophic form, preserving the *T*, *I* and *F* components associated with each relationship. This matrix constitutes the direct input to the crispification procedure and serves as the basis for the subsequent DEMATEL analysis. Notably, the influence level assigned by the experts was expressed using the conventional DEMATEL scale from 0 to 4, while the accompanying *T*, *I* and *F* components captured the experts' confidence, indeterminacy and falsity associated with each assessment. Consequently, the original DEMATEL scale values could, in principle, also be used as inputs for a conventional DEMATEL calculation. However, the present study does not aim to establish that the neutrosophic formulation produces superior results relative to the conventional approach. Rather, the neutrosophic formulation was adopted

Table 3
Direct-relation matrix *Z* with neutrosophic values for advantages.

	V1	V2	V3	V4	V5	V6	V7	V8	V9
V1	–	4 (0.8; 0.2; 0.1)	4 (0.9; 0.2; 0.1)	2 (0.3; 0.6; 0.3)	4 (0.8; 0.2; 0.1)	4 (0.8; 0.2; 0.1)	4 (0.3; 0.8; 0.3)	2 (0.4; 0.7; 0.4)	4 (0.7; 0.3; 0.2)
V2	2 (0.7; 0.3; 0.2)	–	1 (0.8; 0.2; 0.2)	1 (0.7; 0.2; 0.2)	4 (0.8; 0.2; 0.1)	4 (0.8; 0.2; 0.1)	4 (0.7; 0.2; 0.1)	4 (0.7; 0.2; 0.1)	4 (0.8; 0.4; 0.2)
V3	2 (0.7; 0.8; 0.3)	2 (0.7; 0.8; 0.3)	–	4 (0.8; 0.4; 0.1)	1 (0.6; 0.5; 0.3)	1 (0.6; 0.5; 0.3)	3 (0.7; 0.6; 0.1)	2 (0.4; 0.8; 0.3)	1 (0.8; 0.1; 0.1)
V4	2 (0.7; 0.8; 0.3)	2 (0.7; 0.8; 0.3)	4 (0.8; 0.4; 0.1)	–	1 (0.6; 0.5; 0.3)	1 (0.6; 0.5; 0.3)	3 (0.7; 0.6; 0.1)	2 (0.4; 0.8; 0.3)	3 (0.8; 0.2; 0.2)
V5	4 (0.9; 0.1; 0.1)	4 (0.9; 0.1; 0.1)	4 (0.9; 0.1; 0.1)	2 (0.8; 0.2; 0.2)	–	4 (0.9; 0.1; 0.1)	4 (0.9; 0.1; 0.1)	4 (0.9; 0.1; 0.1)	4 (0.9; 0.1; 0.1)
V6	4 (0.9; 0.1; 0.1)	4 (0.9; 0.1; 0.1)	4 (0.9; 0.1; 0.1)	4 (0.9; 0.1; 0.1)	4 (0.9; 0.1; 0.1)	–	4 (0.9; 0.1; 0.1)	4 (0.9; 0.1; 0.1)	4 (0.9; 0.1; 0.1)
V7	1 (0.7; 0.2; 0.2)	3 (0.8; 0.1; 0.2)	1 (0.7; 0.3; 0.3)	2 (0.4; 0.7; 0.4)	4 (0.9; 0.1; 0.1)	4 (0.9; 0.1; 0.1)	–	3 (0.8; 0.3; 0.3)	3 (0.8; 0.3; 0.3)
V8	3 (0.8; 0.2; 0.2)	3 (0.8; 0.2; 0.2)	2 (0.7; 0.2; 0.3)	2 (0.7; 0.2; 0.3)	4 (0.9; 0.1; 0.1)	4 (0.9; 0.1; 0.1)	4 (0.9; 0.1; 0.1)	–	4 (0.9; 0.1; 0.1)
V9	4 (0.9; 0.1; 0.1)	4 (0.9; 0.1; 0.1)	4 (0.9; 0.1; 0.1)	4 (0.9; 0.1; 0.1)	4 (0.9; 0.1; 0.1)	4 (0.9; 0.1; 0.1)	4 (0.9; 0.1; 0.1)	4 (0.9; 0.1; 0.1)	–

to explicitly incorporate uncertainty into the expert-elicitation process before the subsequent DEMATEL analysis. Furthermore, the recurrence of identical *T*, *I* and *F* values across several relationships reflects the expert panel's assessments and is not imposed by the neutrosophic procedure. Similar values may arise when experts perceive different relationships as having comparable levels of confidence, indeterminacy and falsity.

After completing the matrix presented in Table 3, the process of transforming the neutrosophic data into single values, known as crispification, was carried out. This step involved aggregating the *T*, *I* and *F* components of each cell to generate the values required for applying the DEMATEL method. The calculations were initially performed using both Equation (1) and (*2*). The resulting outputs proved highly consistent and did not alter the interpretation of the results. However, following a collective assessment of the resulting outputs, the expert panel considered the values obtained through Equation (1) to be more closely aligned with their understanding of the problem context and, therefore, adopted this formulation for the subsequent analysis. For instance, when a relationship between criteria is represented by *x*(1; 0; 0), the crispified value remains equal to *x*, as the degree of truth is absolute and there is no associated indeterminacy or falsity. The values obtained from this crispification process are presented in Table 4, which serves as the foundation for analyzing the perceived causal relationships in the proposed analytic system. Importantly, more than two decimal places appear only in intermediate computational stages, namely during the crispification of neutrosophic evaluations and the construction of the matrices *T*. They were retained to preserve computational accuracy and avoid cumulative rounding effects that could influence subsequent calculations.

In the next step, the initial direct influence matrix was constructed, as presented in Table 5. This matrix was derived from the conversion of neutrosophic values into crispified values, as described above, and serves as the foundation for performing Steps 2 through 6 of the DEMATEL method (see Section 3).

Table 6 presents the values obtained during the intermediate calculation phase, derived from the application of Equation (4) and (5) described in Section 3. These calculations were essential for normalizing the initial direct influence matrix (Step 2), as required in the second stage of the DEMATEL method. The outcome of this normalization process is shown in Table 7.

The matrices *I*, *I-X* and $(I\text{-}X)^{-1}$, presented in Table 8, were used to construct the total influence matrix *T*, also shown in Table 8. This matrix was derived from Equation (6) (see Section 3). The total relationship matrix *T* plays an essential role in understanding the interactions between the criteria, emphasizing the sums by row (*R*) and by column (*C*), as described in *Step 4* of the methodology.

In the influence analysis, column *R* indicates the capacity of each factor to impact the others, with *High customization capacity* (V9) standing out at a value of 2.6882 as the advantage that exerts the greatest influence on the rest. Conversely, row *C* reflects the total influence that the remaining advantages have on a given factor, highlighting the advantage most affected by the others, which in this case is also V9 with a value of 1.9877. At this stage, a threshold value (α) is defined, calculated as the average of the values in matrix *T* (see Equation (9)). Here, $\alpha = 0.2735$ represents the threshold that identifies the most influential relationships and the most relevant values, which are highlighted in green in matrix *T* (Table 8).

This step is crucial for constructing the IRM. To interpret the IRM, it is essential to consider the sums and differences of *R* and *C* for each variable, as presented in Table 9.

Considering that the value $R + C$ represents the overall relevance of an advantage within the system, it can be associated with the horizontal axis of the diagram. The higher the value along this axis, the greater the factor's impact on the final analytic system. In this context, *High capacity for personalization* (V9) emerges as the most important advantage, with $R + C = 4.6758$, while V4 – *Personalized experience for training and development* – is the least relevant, with $R + C = 2.3613$. The analysis of $R-C$, which measures the net influence of an advantage on the system relative to other advantages, allows for classification into two groups: (1) *causes*, where $R-C > 0$; and (2) *effects*, where $R-C < 0$, based on their position along the vertical axis of the diagram. Fig. 3 illustrates the IRM, showing the distribution of the nine advantages along the corresponding axes and enabling the identification of the established causal relationships.

As can be seen, most advantages belong to the group of causes, indicating that they exert influence on other factors and maintain strong interrelationships. The exceptions are: *Educational and didactic aspect* (V3), *Personalized experience for training and development* (V4) and *Monitoring and improvement of work processes* (V7), respectively, which are primarily receiving advantages, meaning they are influenced by others and demonstrate weaker relational impact. Fig. 3 (*i.e.*, Step 6) not only illustrates the order of relevance of each advantage (V9 > V6 > V5 > V8 > V2 > V7 > V1 > V3 > V4) but also classifies them within the quadrants of the diagram: core factors (QI) include V1, V2, V5, V6, V8 and V9; independent factors (QIII) include V3 and V4; and V7 is an impact factor (QIV), reflecting its position in the influence map. It is important to note that the prominence and causal measures obtained through DEMATEL are derived from matrix *T* rather than from matrix *Z* alone. It should also be recognized that criteria receiving consistently high direct influence assessments from experts are expected to exhibit greater prominence within a DEMATEL analysis. In this study, V6 (*Time saving and full availability*) and V9 (*High personalization capacity*) received comparatively strong evaluations in the direct-relation matrix *Z*, reflecting the panel's perception that these advantages affect multiple aspects of TA-based management. However, their final positions are not determined solely by these direct assessments. The prominence values reported in Table 9 derive from the total-relation matrix *T*, which incorporates both direct and indirect pathways of influence. Consequently, the rankings should be interpreted as representations of the influence structure perceived by the expert panel rather than as a simple reproduction of the original row values in matrix *Z*.

The methodological process was then repeated, this time focusing on the second aspect of the study (*i.e.*, the disadvantages of TA-based management). The analysis began with the disadvantages identified by the expert panel during the structuring phase (see Table 2). The neutrosophic values assigned in the second session are presented in

Table 4
Neutrosophic values crispification – advantages.

	Relationship Analyzed	DEMATEL Scale (x)	Neutrosophic Values (*T*, *I*, *F*)			Neutrosophic Crispification		
			T	I	F	Crispification Equation Numerator	Crispification Weight *w*	Final Value in Matrix *X*
ADVANTAGES (V)	V1-V2	4.0	0.80	0.20	0.10	0.827	0.015	3.307
	V1-V3	4.0	0.90	0.20	0.10	0.859	0.016	3.434
	V1-V4	2.0	0.30	0.60	0.30	0.440	0.008	0.880
	V1-V5	4.0	0.80	0.20	0.10	0.827	0.015	3.307
	V1-V6	4.0	0.80	0.20	0.10	0.827	0.015	3.307
	V1-V7	4.0	0.30	0.80	0.30	0.362	0.007	1.449
	V1-V8	2.0	0.40	0.70	0.40	0.420	0.008	0.840
	V1-V9	4.0	0.70	0.30	0.20	0.729	0.013	2.917
	V2-V1	2.0	0.70	0.30	0.20	0.729	0.013	1.458
	V2-V3	1.0	0.80	0.20	0.20	0.800	0.015	0.800
	V2-V4	1.0	0.70	0.20	0.20	0.762	0.014	0.762
	V2-V5	4.0	0.80	0.20	0.10	0.827	0.015	3.307
	V2-V6	4.0	0.80	0.20	0.10	0.827	0.015	3.307
	V2-V7	4.0	0.70	0.20	0.10	0.784	0.014	3.136
	V2-V8	4.0	0.70	0.20	0.10	0.784	0.014	3.136
	V2-V9	4.0	0.80	0.40	0.20	0.717	0.013	2.869
	V3-V1	2.0	0.70	0.80	0.30	0.477	0.009	0.954
	V3-V2	2.0	0.70	0.80	0.30	0.477	0.009	0.954
	V3-V4	4.0	0.80	0.40	0.10	0.735	0.013	2.942
	V3-V5	1.0	0.60	0.50	0.30	0.592	0.011	0.592
	V3-V6	1.0	0.60	0.50	0.30	0.592	0.011	0.592
	V3-V7	3.0	0.70	0.60	0.10	0.608	0.011	1.825
	V3-V8	2.0	0.40	0.80	0.30	0.397	0.007	0.794
	V3-V9	1.0	0.80	0.10	0.10	0.859	0.016	0.859
	V4-V1	2.0	0.70	0.80	0.30	0.477	0.009	0.954
	V4-V2	2.0	0.70	0.80	0.30	0.477	0.009	0.954
	V4-V3	4.0	0.80	0.40	0.10	0.735	0.013	2.942
	V4-V5	1.0	0.60	0.50	0.30	0.592	0.011	0.592
	V4-V6	1.0	0.60	0.50	0.30	0.592	0.011	0.592
	V4-V7	3.0	0.70	0.60	0.10	0.608	0.011	1.825
	V4-V8	2.0	0.40	0.80	0.30	0.397	0.007	0.794
	V4-V9	3.0	0.80	0.20	0.20	0.800	0.015	2.400
	V5-V1	4.0	0.90	0.10	0.10	0.900	0.016	3.600
	V5-V2	4.0	0.90	0.10	0.10	0.900	0.016	3.600
	V5-V3	4.0	0.90	0.10	0.10	0.900	0.016	3.600
	V5-V4	2.0	0.80	0.20	0.20	0.800	0.015	1.600
	V5-V6	4.0	0.90	0.10	0.10	0.900	0.016	3.600
	V5-V7	4.0	0.90	0.10	0.10	0.900	0.016	3.600
	V5-V8	4.0	0.90	0.10	0.10	0.900	0.016	3.600
	V5-V9	4.0	0.90	0.10	0.10	0.900	0.016	3.600
	V6-V1	4.0	0.90	0.10	0.10	0.900	0.016	3.600
	V6-V2	4.0	0.90	0.10	0.10	0.900	0.016	3.600
	V6-V3	4.0	0.90	0.10	0.10	0.900	0.016	3.600
	V6-V4	4.0	0.90	0.10	0.10	0.900	0.016	3.600
	V6-V5	4.0	0.90	0.10	0.10	0.900	0.016	3.600
	V6-V7	4.0	0.90	0.10	0.10	0.900	0.016	3.600
	V6-V8	4.0	0.90	0.10	0.10	0.900	0.016	3.600
	V6-V9	4.0	0.90	0.10	0.10	0.900	0.016	3.600
	V7-V1	1.0	0.70	0.20	0.20	0.762	0.014	0.762
	V7-V2	3.0	0.80	0.10	0.20	0.827	0.015	2.480
	V7-V3	1.0	0.70	0.30	0.30	0.700	0.013	0.700
	V7-V4	2.0	0.40	0.70	0.40	0.420	0.008	0.840
	V7-V5	4.0	0.90	0.10	0.10	0.900	0.016	3.600
	V7-V6	4.0	0.90	0.10	0.10	0.900	0.016	3.600
	V7-V8	3.0	0.80	0.30	0.30	0.729	0.013	2.188
	V7-V9	3.0	0.80	0.30	0.30	0.729	0.013	2.188
	V8-V1	3.0	0.80	0.20	0.20	0.800	0.015	2.400
	V8-V2	3.0	0.80	0.20	0.20	0.800	0.015	2.400
	V8-V3	2.0	0.70	0.20	0.30	0.729	0.013	1.458
	V8-V4	2.0	0.70	0.20	0.30	0.729	0.013	1.458
	V8-V5	4.0	0.90	0.10	0.10	0.900	0.016	3.600
	V8-V6	4.0	0.90	0.10	0.10	0.900	0.016	3.600
	V8-V7	4.0	0.90	0.10	0.10	0.900	0.016	3.600
	V8-V9	4.0	0.90	0.10	0.10	0.900	0.016	3.600
	V9-V1	4.0	0.90	0.10	0.10	0.900	0.016	3.600
	V9-V2	4.0	0.90	0.10	0.10	0.900	0.016	3.600
	V9-V3	4.0	0.90	0.10	0.10	0.900	0.016	3.600
	V9-V4	4.0	0.90	0.10	0.10	0.900	0.016	3.600
	V9-V5	4.0	0.90	0.10	0.10	0.900	0.016	3.600
	V9-V6	4.0	0.90	0.10	0.10	0.900	0.016	3.600
	V9-V7	4.0	0.90	0.10	0.10	0.900	0.016	3.600

(*continued on next page*)

Table 4 (*continued*)

	Relationship Analyzed	DEMATEL Scale (x)	Neutrosophic Values (*T*, *I*, *F*)			Neutrosophic Crispification		
			T	I	F	Crispification Equation Numerator	Crispification Weight *w*	Final Value in Matrix *X*
	V9-V8	4.0	0.90	0.10	0.10	0.900	0.016	3.600
If $S = 1$, the relevant conditions are respected.					Crispification Equation Denominator	**55.062**	**1**	

Table 5
Initial matrix of direct influence – advantages.

	V1	V2	V3	V4	V5	V6	V7	V8	V9	Total
V1	0.00	3.31	3.43	0.88	3.31	3.31	1.45	0.84	2.92	19.4
V2	1.46	0.00	0.80	0.76	3.31	3.31	3.14	3.14	2.87	18.8
V3	0.95	0.95	0.00	2.94	0.59	0.59	1.83	0.79	0.86	9.5
V4	0.95	0.95	2.94	0.00	0.59	0.59	1.83	0.79	2.40	11.1
V5	3.60	3.60	3.60	1.60	0.00	3.60	3.60	3.60	3.60	26.8
V6	3.60	3.60	3.60	3.60	3.60	0.00	3.60	3.60	3.60	28.8
V7	0.76	2.48	0.70	0.84	3.60	3.60	0.00	2.19	2.19	16.4
V8	2.40	2.40	1.46	1.46	3.60	3.60	3.60	0.00	3.60	22.1
V9	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60	0.00	28.8
Total	17.3	20.9	20.1	15.7	22.2	22.2	22.6	18.6	22.0	

Table 6
Intermediate calculations – advantages.

Max.	22.6	28.8
1/max.	0.0441785	0.0347222
1/s	**0.0347222**	

Table 10 and were subsequently crispified, as shown in Table 11.

Next, the crispification of the neutrosophic values enabled the construction of the initial direct influence matrix, with the corresponding crispified values presented in Table 12. Following the intermediate calculations (see Table 13,Table 14 andTable 15), Table 16 was obtained, showing that the disadvantage exerting the greatest influence on the others is *Associated costs* (D9), with an *R* value (*i.e.*, total influence) of 1.5498. Conversely, *Difficulty in people management* (D10), with a *C* value of 1.0701, is the disadvantage most affected by the others.

After calculating the total relationship matrix *T* (Table 15), the row and column sums were computed, with the results presented in Table 16.

Fig. 4 illustrates the importance of each disadvantage, based on the $R + C$ values, as follows: D9 > D6 > D1 > D7 > D10 > D4 > D8 > D5 > D2 > D3. In this context, *Associated costs* (D9) emerges as the most significant disadvantage, with an $R + C$ value of 2.0292. Disadvantages with a positive $R-C$ value indicate that they exert more influence than they receive and, therefore, belong to the group of causes: D1, D6, D7 and D9. Conversely, D2, D3, D4, D5, D8 and D10, positioned lower in the diagram, are classified as effects, as they predominantly receive influence from other factors. Furthermore, Fig. 4 (*i.e.*, Step 6) facilitates the classification of disadvantages across the quadrants of the diagram: (1) core factors (QI) include D1, D6 and D9; (2) D7 is a driving factor (QII); (3) independent factors (QIII) include D2, D3, D4, D5 and D8; (4) and D10 is identified as an impact factor (QIV).

As shown in Fig. 4, although D9 received high influence assessments from the experts in the direct-relation matrix *Z*, its prominence in the final results reflects not only these evaluations but also the indirect influences propagated throughout the network of disadvantages. Therefore, the position of D9 should not be interpreted merely as an artifact of high row values in matrix *Z*, but as an indication that the expert panel perceived costs as a central element affecting multiple interconnected disadvantages associated with TA-based management.

Importantly, during the facilitated sessions, interactive sensitivity exercises were embedded in the group discussions. Alternative judgments were explored and, where appropriate, values were modified so that the panel could immediately observe and discuss the implications of these changes for the resulting influence relationships among the factors. This iterative process allowed participants to challenge, reconsider and negotiate individual assessments and to refine the collective representation of the causal structure. This exercise therefore provided an interactive assessment of the consequences of alternative judgments during the expert-elicitation process, contributing to the validation and consolidation of the final influence matrices. This procedure should be distinguished from a formal *post-hoc* sensitivity analysis based on systematically defined parameter variations; rather, it formed part of the facilitated assessment and validation process itself. Once the assessment phase of the problem was completed, the study proceeded to the discussion and recommendations stage.

4.3. Consolidation, discussion and recommendations

A consolidation session was held to reinforce the credibility of the analysis and obtain an external, impartial and technically grounded assessment of its practical applicability. Although relying on a single expert, this external consolidation procedure was designed to provide an independent appraisal of the analytic system developed by the panel. Rather than serving as statistical triangulation, its purpose was to examine the credibility, coherence, practical relevance and transferability of the framework from the perspective of a knowledgeable practitioner who had not participated in the model construction process. Such a procedure is consistent with process-oriented intervention research, where the objective is to evaluate the usefulness and robustness of the decision-support framework rather than to verify statistical generalizability (cf. Bell & Morse, 2013; Gregory et al., 2020; Gil et al., 2026; Macedo et al., 2024). The session provided an opportunity to critically assess the robustness of the analytic system, verify the

Table 7
Normalized direct influence matrix or Matrix X – advantages.

	V1	V2	V3	V4	V5	V6	V7	V8	V9
V1	0.00	0.11	0.12	0.03	0.11	0.11	0.05	0.03	0.10
V2	0.05	0.00	0.03	0.03	0.11	0.11	0.11	0.11	0.10
V3	0.03	0.03	0.00	0.10	0.02	0.02	0.06	0.03	0.03
V4	0.03	0.03	0.10	0.00	0.02	0.02	0.06	0.03	0.08
V5	0.13	0.13	0.13	0.06	0.00	0.13	0.13	0.13	0.13
V6	0.13	0.13	0.13	0.13	0.13	0.00	0.13	0.13	0.13
V7	0.03	0.09	0.02	0.03	0.13	0.13	0.00	0.08	0.08
V8	0.08	0.08	0.05	0.05	0.13	0.13	0.13	0.00	0.13
V9	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.00

Table 8
Matrix *T* and corresponding intermediate calculations – Advantages.

I	**V1**	**V2**	**V3**	**V4**	**V5**	**V6**	**V7**	**V8**	**V9**
V1	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
V2	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
V3	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
V4	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
V5	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
V6	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00
V7	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00
V8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
V9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00

$(I\text{-}X)^{-1}$	**V1**	**V2**	**V3**	**V4**	**V5**	**V6**	**V7**	**V8**	**V9**
V1	1.18	0.31	0.30	0.19	0.32	0.32	0.27	0.22	0.30
V2	0.23	1.22	0.23	0.19	0.33	0.33	0.33	0.30	0.31
V3	0.10	0.12	1.08	0.16	0.11	0.11	0.15	0.11	0.12
V4	0.12	0.14	0.20	1.09	0.13	0.13	0.17	0.12	0.18
V5	0.34	0.39	0.37	0.26	1.29	0.40	0.41	0.36	0.39
V6	0.35	0.39	0.38	0.33	0.41	1.30	0.42	0.37	0.40
V7	0.19	0.27	0.20	0.17	0.32	0.32	1.21	0.25	0.27
V8	0.28	0.32	0.28	0.23	0.37	0.37	0.37	1.22	0.36
V9	0.35	0.39	0.38	0.33	0.41	0.41	0.42	0.37	1.29

I-X	**V1**	**V2**	**V3**	**V4**	**V5**	**V6**	**V7**	**V8**	**V9**
V1	1.00	-0.11	-0.12	-0.03	-0.11	-0.11	-0.05	-0.03	-0.10
V2	-0.05	1.00	-0.03	-0.03	-0.11	-0.11	-0.11	-0.11	-0.10
V3	-0.03	-0.03	1.00	-0.10	-0.02	-0.02	-0.06	-0.03	-0.03
V4	-0.03	-0.03	-0.10	1.00	-0.02	-0.02	-0.06	-0.03	-0.08
V5	-0.13	-0.13	-0.13	-0.06	1.00	-0.13	-0.13	-0.13	-0.13
V6	-0.13	-0.13	-0.13	-0.13	-0.13	1.00	-0.13	-0.13	-0.13
V7	-0.03	-0.09	-0.02	-0.03	-0.13	-0.13	1.00	-0.08	-0.08
V8	-0.08	-0.08	-0.05	-0.05	-0.13	-0.13	-0.13	1.00	-0.13
V9	-0.13	-0.13	-0.13	-0.13	-0.13	-0.13	-0.13	-0.13	1.00

Matrix *T*	**V1**	**V2**	**V3**	**V4**	**V5**	**V6**	**V7**	**V8**	**V9**	***R***
V1	0.1753	0.3106	0.3036	0.1897	0.3198	0.3198	0.2695	0.2199	0.3027	1.8883
V2	0.2315	0.2162	0.2262	0.1865	0.3341	0.3341	0.3301	0.2983	0.3127	1.8587
V3	0.1035	0.1185	0.0846	0.1624	0.1127	0.1127	0.1536	0.1053	0.1212	0.8481
V4	0.1205	0.1377	0.1957	0.0856	0.1327	0.1327	0.1738	0.1232	0.1840	0.9787
V5	0.3422	0.3861	0.3672	0.2596	0.2918	0.4029	0.4051	0.3611	0.3934	2.4549
V6	0.3496	0.3946	0.3793	0.3266	0.4111	0.3000	0.4159	0.3687	0.4048	2.5771
V7	0.1916	0.2718	0.2026	0.1722	0.3161	0.3161	0.2068	0.2498	0.2688	1.6772
V8	0.2827	0.3211	0.2750	0.2302	0.3707	0.3707	0.3720	0.2233	0.3618	2.2224
V9	0.3496	0.3946	0.3793	0.3266	0.4111	0.4111	0.4159	0.3687	0.2937	2.6882
C	1.5140	1.8355	1.7592	1.3826	1.9183	1.9183	1.9549	1.7264	1.9877	

relevance of the identified advantages and disadvantages and evaluate the applicability of the methodologies employed (*i.e.*, NGT and DEMATEL in a neutrosophic environment). In doing so, it helped ensure that the findings are not only theoretically sound but also practically meaningful, offering guidance for decision-making in real-world organizational contexts while maintaining a focus on human-centered considerations.

This session, like the previous ones, was conducted online and lasted approximately 1 h, with the participation of a representative from Altice Labs, who possesses extensive experience in technological innovation, particularly in smart cities, IoT, AI, TAs and digital transformation. As the expert was not involved in the analytic system development, he was

Table 9
Interactions – advantages.

	R	C	R + C	R–C
V1	1.8883	1.5140	3.4024	0.3743
V2	1.8587	1.8355	3.6941	0.0232
V3	0.8481	1.7592	2.6073	−0.9111
V4	0.9787	1.3826	2.3613	−0.4039
V5	2.4549	1.9183	4.3733	0.5366
V6	2.5771	1.9183	4.4954	0.6587
V7	1.6772	1.9549	3.6322	−0.2777
V8	2.2224	1.9549	4.1773	0.2674
V9	2.6882	1.9877	4.6758	0.7005

considered neutral, ensuring an independent evaluation of the findings (cf. Gil et al., 2026). The following structured agenda was followed: (1) a brief overview of the concepts and objectives of the study; (2) presentation of the methodological approach; (3) demonstration of the techniques applied and the results obtained; (4) expert perceptions of the methodologies; (5) feedback on the results; (6) evaluation of the practical applicability of the analytic system; and (7) suggestions for improvement and recommendations.

Despite not being deeply familiar with the methodologies applied, the expert recognized parallels with approaches he regularly uses, considering the structure employed in this study to be consistent with real-world decision-making processes. Importantly, his comment regarding limited familiarity referred exclusively to some of the techniques employed and should not be interpreted as indicating a lack of expertise in the substantive domain under analysis, in which he possesses extensive professional experience. He viewed the overall framework as a coherent and useful tool for analyzing complex and interrelated criteria, emphasizing the transparency and traceability afforded by the integration of NGT and DEMATEL.

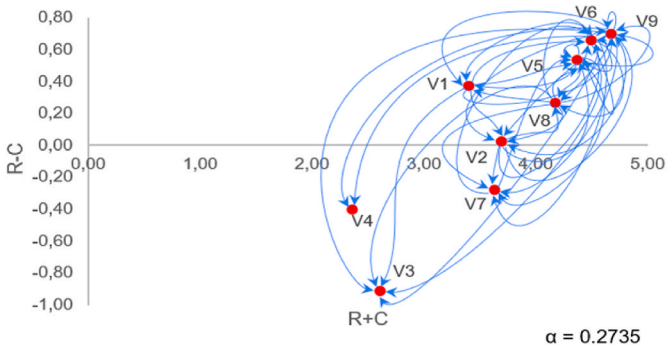


Fig. 3. Influence relation map – advantages.

Regarding the identified advantages, the expert provided nuanced feedback. He highlighted that the advantage related to *High personalization capacity* (V9) might be paradoxical, as TAs could, in some contexts, depersonalize interactions. He questioned the *Educational and didactic advantage* (V3) in relation to the abundant online resources available, suggesting that its added value may be context-dependent. The advantage of *Time savings* (V6) was also discussed critically, especially in scenarios where TAs are used exclusively, noting that human intervention remains necessary in certain complex tasks. These observations did not invalidate the identified advantages but rather introduced contextual considerations that help qualify and refine their interpretation. As the expert clearly mentioned, *"the potential of TAs to optimize routine operations, enhance operational management, monitor work processes and provide personalized training experiences is widely recognized"* (in his words). Additionally, the expert stressed the importance of preserving human presence and interaction in certain operations, even when knowledge and decision-making scalability is achieved.

On the disadvantages, the expert underscored concerns regarding *Personal data* and *Privacy* (D1 and D2), and [the risk of algorithmic] *Bias* (D8), which could shape distorted perceptions and decision outcomes. He emphasized potential *Loss of creative freedom* (D3), negative emotional impacts and the erosion of uniquely human qualities in interactions, reinforcing the need for ethical oversight. The expert advocated for balancing technological advancement with the preservation of human judgment and critical thinking.

When discussing practical implementation, he highlighted the importance of evaluating the cost-benefit trade-offs of adopting TA-based systems and maintaining the central role of humans in decision-making processes. The structured visualization of causal relationships, as presented in the IRMs, was praised for providing decision-makers with a clear understanding of how advantages and disadvantages interact, supporting more informed and strategic choices.

Overall, the expert expressed a very positive view of the proposed analytic system, noting that *"it effectively combines rigor, transparency and practical relevance"* (in his words). He appreciated the structured approach, which allows decision-makers to visualize complex interdependencies clearly, while also accommodating expert judgment and uncertainty through the neutrosophic framework. In his words, the system *"offers a comprehensive yet flexible tool for analyzing the multifaceted implications of TA-based management"*, highlighting its potential as both a decision-support mechanism and a learning platform for

Table 10
Direct-relation matrix Z with neutrosophic values for disadvantages.

	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10
D1	–	4 (0.9; 0.1; 0.1)	0 (0.9; 0.1; 0.1)	2 (0.7; 0.3; 0.3)	0 (0.8; 0.1; 0.2)	4 (0.8; 0.4; 0.2)	4 (0.9; 0.1; 0.1)	4 (0.8; 0.3; 0.2)	4 (0.9; 0.1; 0.1)	2 (0.7; 0.7; 0.2)
D2	1 (0.7; 0.4; 0.4)	–	0 (0.9; 0.1; 0.1)	0 (0.9; 0.1; 0.1)	0 (0.9; 0.1; 0.1)	0 (0.9; 0.1; 0.1)	0 (0.9; 0.1; 0.1)	0 (0.9; 0.1; 0.1)	3 (0.9; 0.2; 0.1)	2 (0.7; 0.6; 0.5)
D3	0 (0.9; 0.1; 0.1)	0 (0.9; 0.1; 0.1)	–	2 (0.7; 0.4; 0.3)	1 (0.4; 0.7; 0.6)	0 (0.9; 0.1; 0.1)	0 (0.9; 0.1; 0.1)	0 (0.9; 0.1; 0.1)	0 (0.9; 0.1; 0.1)	2 (0.7; 0.6; 0.5)
D4	0 (0.9; 0.1; 0.1)	0 (0.9; 0.1; 0.1)	3 (0.8; 0.2; 0.1)	–	4 (0.9; 0.1; 0.1)	3 (0.7; 0.4; 0.3)	0 (0.9; 0.1; 0.1)	0 (0.9; 0.1; 0.1)	0 (0.9; 0.1; 0.1)	4 (0.9; 0.2; 0.1)
D5	0 (0.9; 0.1; 0.1)	0 (0.9; 0.1; 0.1)	2 (0.7; 0.4; 0.4)	3 (0.7; 0.7; 0.4)	–	2 (0.7; 0.3; 0.4)	3 (0.9; 0.5; 0.5)	0 (0.9; 0.1; 0.1)	0 (0.9; 0.1; 0.1)	4 (0.9; 0.2; 0.1)
D6	3 (0.8; 0.1; 0.1)	3 (0.8; 0.1; 0.1)	3 (0.8; 0.1; 0.1)	3 (0.8; 0.1; 0.1)	3 (0.8; 0.1; 0.1)	–	3 (0.8; 0.1; 0.1)	3 (0.8; 0.1; 0.1)	0 (0.9; 0.1; 0.1)	4 (0.9; 0.2; 0.1)
D7	4 (0.9; 0.1; 0.1)	4 (0.9; 0.1; 0.1)	0 (0.9; 0.1; 0.1)	1 (0.7; 0.5; 0.5)	0 (0.9; 0.1; 0.1)	0 (0.9; 0.1; 0.1)	–	3 (0.8; 0.3; 0.3)	4 (0.9; 0.1; 0.1)	3 (0.9; 0.1; 0.1)
D8	0 (0.9; 0.1; 0.1)	0 (0.9; 0.1; 0.1)	3 (0.8; 0.2; 0.2)	3 (0.8; 0.2; 0.2)	0 (0.9; 0.1; 0.1)	2 (0.8; 0.2; 0.2)	0 (0.9; 0.1; 0.1)	–	0 (0.9; 0.1; 0.1)	3 (0.8; 0.2; 0.2)
D9	4 (0.9; 0.1; 0.1)	4 (0.9; 0.1; 0.1)	4 (0.9; 0.1; 0.1)	4 (0.9; 0.1; 0.1)	4 (0.9; 0.1; 0.1)	4 (0.9; 0.1; 0.1)	4 (0.9; 0.1; 0.1)	4 (0.9; 0.1; 0.1)	–	4 (0.9; 0.1; 0.1)
D10	0 (0.9; 0.1; 0.1)	1 (0.5; 0.9; 0.5)	3 (0.7; 0.7; 0.7)	2 (0.7; 0.5; 0.5)	0 (0.9; 0.3; 0.1)	3 (0.9; 0.1; 0.1)	0 (0.9; 0.1; 0.1)	0 (0.9; 0.1; 0.1)	1 (0.5; 0.9; 0.5)	–

Table 11
Neutrosophic values crispification – disadvantages.

	Relationship Analyzed	DEMATEL Scale (x)	Neutrosophic Values			Neutrosophic Crispification		
			T	I	F	Crispification Equation Numerator	Crispification Weight *w*	Final Value in Matrix *X*
DISADVANTAGES (D)	D1-D2	4.0	0.90	0.10	0.10	0.900	0.012	3.600
	D1-D3	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D1-D4	2.0	0.70	0.30	0.30	0.700	0.010	1.400
	D1-D5	0.0	0.80	0.10	0.20	0.827	0.011	0.000
	D1-D6	4.0	0.80	0.40	0.20	0.717	0.010	2.869
	D1-D7	4.0	0.90	0.10	0.10	0.900	0.012	3.600
	D1-D8	4.0	0.80	0.30	0.20	0.762	0.010	3.048
	D1-D9	4.0	0.90	0.10	0.10	0.900	0.012	3.600
	D1-D10	2.0	0.70	0.70	0.20	0.545	0.007	1.091
	D2-D1	1.0	0.70	0.40	0.40	0.630	0.009	0.630
	D2-D3	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D2-D4	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D2-D5	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D2-D6	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D2-D7	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D2-D8	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D2-D9	3.0	0.90	0.20	0.10	0.859	0.012	2.576
	D2-D10	2.0	0.70	0.60	0.50	0.517	0.007	1.034
	D3-D1	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D3-D2	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D3-D4	2.0	0.70	0.40	0.30	0.663	0.009	1.327
	D3-D5	1.0	0.40	0.70	0.60	0.365	0.005	0.365
	D3-D6	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D3-D7	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D3-D8	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D3-D9	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D3-D10	2.0	0.70	0.60	0.50	0.517	0.007	1.034
	D4-D1	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D4-D2	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D4-D3	3.0	0.80	0.20	0.10	0.827	0.011	2.480
	D4-D5	4.0	0.90	0.10	0.10	0.900	0.012	3.600
	D4-D6	3.0	0.70	0.40	0.30	0.663	0.009	1.990
	D4-D7	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D4-D8	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D4-D9	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D4-D10	4.0	0.90	0.20	0.10	0.859	0.012	3.434
	D5-D1	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D5-D2	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D5-D3	2.0	0.70	0.40	0.40	0.630	0.009	1.261
	D5-D4	3.0	0.70	0.70	0.40	0.503	0.007	1.510
	D5-D6	2.0	0.70	0.30	0.40	0.663	0.009	1.327
	D5-D7	3.0	0.90	0.50	0.50	0.588	0.008	1.763
	D5-D8	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D5-D9	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D5-D10	4.0	0.90	0.20	0.10	0.859	0.012	3.434
	D6-D1	3.0	0.80	0.10	0.10	0.859	0.012	2.576
	D6-D2	3.0	0.80	0.10	0.10	0.859	0.012	2.576
	D6-D3	3.0	0.80	0.10	0.10	0.859	0.012	2.576
	D6-D4	3.0	0.80	0.10	0.10	0.859	0.012	2.576
	D6-D5	3.0	0.80	0.10	0.10	0.859	0.012	2.576
	D6-D7	3.0	0.80	0.10	0.10	0.859	0.012	2.576
	D6-D8	3.0	0.80	0.10	0.10	0.859	0.012	2.576
	D6-D9	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D6-D10	4.0	0.90	0.20	0.10	0.859	0.012	3.434
	D7-D1	4.0	0.90	0.10	0.10	0.900	0.012	3.600
	D7-D2	4.0	0.90	0.10	0.10	0.900	0.012	3.600
	D7-D3	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D7-D4	1.0	0.70	0.50	0.50	0.557	0.008	0.557
	D7-D5	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D7-D6	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D7-D8	3.0	0.80	0.30	0.30	0.729	0.010	2.188
	D7-D9	4.0	0.90	0.10	0.10	0.900	0.012	3.600
	D7-D10	3.0	0.90	0.10	0.10	0.900	0.012	2.700
	D8-D1	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D8-D2	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D8-D3	3.0	0.80	0.20	0.20	0.800	0.011	2.400
	D8-D4	3.0	0.80	0.20	0.20	0.800	0.011	2.400
	D8-D5	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D8-D6	2.0	0.80	0.20	0.20	0.800	0.011	1.600
	D8-D7	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D8-D9	0.0	0.90	0.10	0.10	0.900	0.012	0.000

(*continued on next page*)

Table 11 (*continued*)

	Relationship Analyzed	DEMATEL Scale (x)	Neutrosophic Values			Neutrosophic Crispification		
			T	I	F	Crispification Equation Numerator	Crispification Weight *w*	Final Value in Matrix *X*
	D8-D10	3.0	0.80	0.20	0.20	0.800	0.011	2.400
	D9-D1	4.0	0.90	0.10	0.10	0.900	0.012	3.600
	D9-D2	4.0	0.90	0.10	0.10	0.900	0.012	3.600
	D9-D3	4.0	0.90	0.10	0.10	0.900	0.012	3.600
	D9-D4	4.0	0.90	0.10	0.10	0.900	0.012	3.600
	D9-D5	4.0	0.90	0.10	0.10	0.900	0.012	3.600
	D9-D6	4.0	0.90	0.10	0.10	0.900	0.012	3.600
	D9-D7	4.0	0.90	0.10	0.10	0.900	0.012	3.600
	D9-D8	4.0	0.90	0.10	0.10	0.900	0.012	3.600
	D9-D10	4.0	0.90	0.10	0.10	0.900	0.012	3.600
	D10-D1	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D10-D2	1.0	0.50	0.90	0.50	0.339	0.005	0.339
	D10-D3	3.0	0.70	0.70	0.70	0.403	0.005	1.208
	D10-D4	2.0	0.70	0.50	0.50	0.557	0.008	1.113
	D10-D5	0.0	0.90	0.30	0.10	0.809	0.011	0.000
	D10-D6	3.0	0.90	0.10	0.10	0.900	0.012	2.700
	D10-D7	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D10-D8	0.0	0.90	0.10	0.10	0.900	0.012	0.000
	D10-D9	1.0	0.50	0.90	0.50	0.339	0.005	0.339
If $S = 1$, the relevant conditions are respected.					Crispification Equation Denominator	**73.295**	**1**	

Table 12
Initial direct influence matrix – disadvantages.

	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	Total
D1	0.00	3.60	0.00	1.40	0.00	2.87	3.60	3.05	3.60	1.09	19.2
D2	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.58	1.03	4.2
D3	0.00	0.00	0.00	1.33	0.36	0.00	0.00	0.00	0.00	1.03	2.7
D4	0.00	0.00	2.48	0.00	3.60	1.99	0.00	0.00	0.00	3.43	11.5
D5	0.00	0.00	1.26	1.51	0.00	1.33	1.76	0.00	0.00	3.43	9.3
D6	2.58	2.58	2.58	2.58	2.58	0.00	2.58	2.58	0.00	3.43	21.5
D7	3.60	3.60	0.00	0.56	0.00	0.00	0.00	2.19	3.60	2.70	16.2
D8	0.00	0.00	2.40	2.40	0.00	1.60	0.00	0.00	0.00	2.40	8.8
D9	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60	0.00	3.60	32.4
D10	0.00	0.34	1.21	1.11	0.00	2.70	0.00	0.00	0.34	0.00	5.7
Total	10.4	13.7	13.5	14.5	10.1	14.1	11.5	11.4	10.1	22.2	

Table 13
Intermediate calculations – disadvantages.

Max	22.2	32.4
1/max	0.0451232	0.0308642
1/s	**0.030864198**	

managers seeking to understand and optimize human-technology interactions. The integration of NGT, DEMATEL and neutrosophic logic was seen as particularly valuable, providing a methodologically robust framework that complements existing models rather than replacing them.

Importantly, the purpose of this consolidation stage was not to confirm the substantive results themselves, but to assess whether the process, structure and outcomes of the analytical framework were considered meaningful, coherent and applicable in practice. In this sense, the study's contribution resides in the transferability of the methodological process. Future applications involving different expert panels, sectors or geographical contexts may generate different contextual results while preserving the underlying methodological logic and analytical rigor.

Confronting the study's results with the literature, the findings confirm and extend prior insights. The identification of advantages such as high personalization, task optimization and operational efficiency

Table 14
Normalized direct influence matrix or Matrix X – disadvantages.

	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10
D1	0.00	0.11	0.00	0.04	0.00	0.09	0.11	0.09	0.11	0.03
D2	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.03
D3	0.00	0.00	0.00	0.04	0.01	0.00	0.00	0.00	0.00	0.03
D4	0.00	0.00	0.08	0.00	0.11	0.06	0.00	0.00	0.00	0.11
D5	0.00	0.00	0.04	0.05	0.00	0.04	0.05	0.00	0.00	0.11
D6	0.08	0.08	0.08	0.08	0.08	0.00	0.08	0.08	0.00	0.11
D7	0.11	0.11	0.00	0.02	0.00	0.00	0.00	0.07	0.11	0.08
D8	0.00	0.00	0.07	0.07	0.00	0.05	0.00	0.00	0.00	0.07
D9	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.00	0.11
D10	0.00	0.01	0.04	0.03	0.00	0.08	0.00	0.00	0.01	0.00

Table 15
Intermediate calculations – Disadvantages.

I	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10
D1	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D2	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D3	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D4	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
D5	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
D6	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
D7	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00
D8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00
D9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
D10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00

$(I\text{-}X)^{-1}$	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10
D1	1.05	0.16	0.05	0.09	0.04	0.13	0.14	0.13	0.15	0.11
D2	0.03	1.02	0.02	0.02	0.01	0.02	0.02	0.02	0.09	0.05
D3	0.00	0.00	1.01	0.04	0.02	0.01	0.00	0.00	0.00	0.04
D4	0.01	0.01	0.10	1.02	0.12	0.08	0.01	0.01	0.00	0.14
D5	0.01	0.02	0.06	0.06	1.01	0.06	0.06	0.01	0.01	0.13
D6	0.10	0.11	0.11	0.12	0.10	1.04	0.10	0.10	0.03	0.16
D7	0.14	0.15	0.04	0.06	0.03	0.05	1.04	0.10	0.14	0.14
D8	0.01	0.01	0.09	0.09	0.02	0.06	0.01	1.01	0.00	0.10
D9	0.15	0.17	0.17	0.17	0.15	0.17	0.16	0.15	1.05	0.21
D10	0.01	0.02	0.05	0.05	0.01	0.09	0.01	0.01	0.01	1.02

I-X	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10
D1	1.00	-0.11	0.00	-0.04	0.00	-0.09	-0.11	-0.09	-0.11	-0.03
D2	-0.02	1.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.08	-0.03
D3	0.00	0.00	1.00	-0.04	-0.01	0.00	0.00	0.00	0.00	-0.03
D4	0.00	0.00	-0.08	1.00	-0.11	-0.06	0.00	0.00	0.00	-0.11
D5	0.00	0.00	-0.04	-0.05	1.00	-0.04	-0.05	0.00	0.00	-0.11
D6	-0.08	-0.08	-0.08	-0.08	-0.08	1.00	-0.08	-0.08	0.00	-0.11
D7	-0.11	-0.11	0.00	-0.02	0.00	0.00	1.00	-0.07	-0.11	-0.08
D8	0.00	0.00	-0.07	-0.07	0.00	-0.05	0.00	1.00	0.00	-0.07
D9	-0.11	-0.11	-0.11	-0.11	-0.11	-0.11	-0.11	-0.11	1.00	-0.11
D10	0.00	-0.01	-0.04	-0.03	0.00	-0.08	0.00	0.00	-0.01	1.00

Matrix T	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	*R*
D1	0.0459	0.1602	0.0492	0.0919	0.0375	0.1317	0.1450	0.1349	0.1462	0.1079	1.0502
D2	0.0327	0.0171	0.0160	0.0170	0.0132	0.0192	0.0155	0.0153	0.0867	0.0514	0.2840
D3	0.0008	0.0013	0.0062	0.0441	0.0169	0.0069	0.0017	0.0008	0.0008	0.0397	0.1192
D4	0.0088	0.0110	0.0957	0.0225	0.1217	0.0809	0.0146	0.0088	0.0049	0.1360	0.5048
D5	0.0132	0.0157	0.0558	0.0624	0.0135	0.0591	0.0625	0.0114	0.0110	0.1303	0.4351
D6	0.1002	0.1109	0.1130	0.1152	0.1006	0.0425	0.1032	0.1029	0.0331	0.1638	0.9854
D7	0.1381	0.1519	0.0381	0.0588	0.0269	0.0493	0.0367	0.1029	0.1440	0.1350	0.8816
D8	0.0064	0.0080	0.0911	0.0883	0.0163	0.0648	0.0071	0.0066	0.0032	0.0968	0.3886
D9	0.1507	0.1664	0.1686	0.1721	0.1513	0.1718	0.1552	0.1549	0.0494	0.2093	1.5498
D10	0.0106	0.0221	0.0522	0.0484	0.0149	0.0919	0.0109	0.0107	0.0149	0.0225	0.2990
C	0.4969	0.6424	0.6338	0.6722	0.4979	0.6261	0.5415	0.5385	0.4794	1.0701	

aligns with prior studies emphasizing TAs' role in enhancing digital interactions, training and operational management (Aiolfi & Luceri, 2024; Silva & Campos, 2024; Zahedi et al., 2022). At the same time, concerns regarding privacy, bias and depersonalization corroborate warnings from Fehrenbacher and Weisner (2024) and Yasuoka et al. (2022) about potential risks in knowledge-sharing and virtual work environments. While some of the identified advantages and disadvantages overlap with those reported in the broader AI literature, their interpretation in the present study is grounded in the specific characteristics of TAs, namely digital embodiment, high personalization capacity, real-time interaction and support for managerial and organizational processes. Moreover, the contribution of this study lies in the development and application of an analytic system for evaluating TA-based management, explicitly accounting for uncertainty, expert knowledge and perceived causal relationships. This contribution resides primarily in the substantive domain and the resulting analytical insights rather than in the proposal of a new methodological procedure. At the same time, to the best of our knowledge, this is the first study to apply this integrated approach specifically to the examination of advantages, disadvantages and causal dynamics associated with TAs in organizational contexts.

The constructivist approach adopted here proved essential in creating a collaborative learning environment, enabling participants to articulate, challenge and refine their perspectives. This iterative process not only generated rich and mature understanding of the advantages and disadvantages of TAs but also fostered knowledge co-creation. Unlike previous models that focus on descriptive analyses or isolated applications of TAs, the present framework offers an interactive, learning-oriented system that allows decision-makers to explore hypothetical scenarios, test causal assumptions and evaluate strategic implications in a risk-free environment. It complements prior models rather than replacing them, providing additional insights into both managerial and organizational dynamics.

The implications of the study are manifold. Theoretically, the results advance understanding of TA-based management by providing an empirically grounded framework for assessing its benefits and limitations, while explicitly considering uncertainty and interdependencies. Specifically, the findings demonstrate that TAs do not merely serve operational or representational functions but act as active agents influencing decision-making processes, organizational learning and strategic adaptation. This aligns with emerging theories on agentic AI, suggesting that such technologies mediate the relationship between human expertise and organizational outcomes, thereby offering a novel lens to understand the co-evolution of digital tools and managerial practice. Practically, organizations can leverage the analytic system to make informed decisions about TA adoption, prioritize initiatives and anticipate potential risks, ultimately supporting more effective and human-centered digital transformation strategies. Societally, the study underscores the ethical, psychological and organizational dimensions of TA deployment, emphasizing the need to preserve human judgment, creativity and privacy, while maximizing efficiency and inclusivity.

In summary, the consolidation session provided additional evidence regarding the coherence, credibility and practical relevance of the analytic system, strengthened confidence in the methodological approach and highlighted the key advantages and challenges associated with TA-based management. The proposed framework serves as both an analytic and a learning tool, facilitating better decision-making and providing organizations with actionable insights into the deployment of TAs in contemporary management contexts. An important characteristic is its constructivist and adaptive nature. As knowledge regarding TA-based management evolves, the framework may be reapplied to incorporate new advantages, disadvantages and contextual factors not identified in the present study. This flexibility allows the analytical structure to evolve alongside technological developments and organizational learning, ensuring its continued relevance in rapidly changing environments.

Table 16
Interactions – disadvantages.

	R	C	R + C	R–C
D1	1.0502	0.4969	1.5471	0.5533
D2	0.2840	0.6424	0.9265	−0.3584
D3	0.1192	0.6338	0.7531	−0.5146
D4	0.5048	0.6722	1.1770	−0.1675
D5	0.4351	0.4979	0.9329	−0.0628
D6	0.9854	0.6261	1.6115	0.3593
D7	0.8816	0.5415	1.4231	0.3402
D8	0.3886	0.5385	0.9272	−0.1499
D9	1.5498	0.4794	2.0292	1.0704
D10	0.2990	1.0701	1.3691	−0.7711

5. Conclusion

TA-based management is increasingly relevant in contemporary organizations, offering opportunities to enhance operational efficiency, competitiveness and the personalization of services. Despite its potential, the adoption of TA technologies remains complex, involving both tangible benefits and inherent challenges. Understanding the advantages and disadvantages of TA-based management is therefore crucial for organizations aiming to integrate this technology effectively while preserving critical human dimensions such as creativity, decision-making and interpersonal interaction.

This study addressed two key gaps in the literature. First, while previous research has highlighted the potential of TAs, there has been limited exploration of the criteria that define their practical advantages and disadvantages in management contexts. Second, existing studies often neglect the role of uncertainty and expert judgment in structuring and analyzing these criteria. In response, this study formulated two research questions: (RQ1) What are the critical advantages and disadvantages of TA-based management?; and (RQ2) How can organizations evaluate the perceived causal relationships among these factors to support informed decision-making?

By integrating NGT, DEMATEL and neutrosophic logic, the study developed a constructivist, multicriteria analytic system that simultaneously captures qualitative insights, causal relationships and uncertainty. The results provided a holistic view of TA-based management. Specifically, the study identified high personalization, operational optimization and scalability of decision-making as the most influential advantages, while highlighting associated costs, data privacy, algorithmic bias and the potential erosion of human creativity as critical disadvantages. This integrated methodological approach allows organizations to visualize and prioritize the interdependencies among factors, offering theoretical and practical insights into TA-based management.

The originality of the framework should be understood in substantive and analytical terms rather than as a claim of methodological invention.

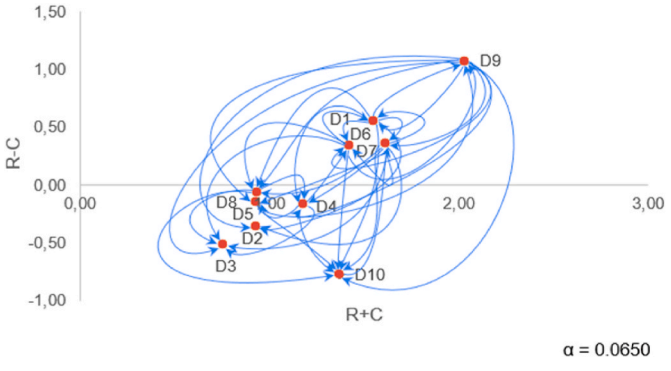


Fig. 4. Influence relation map – disadvantages.

The methodological components employed in the study are established approaches in the MCDA literature. Their value in the present research stems from their application to TA-based management and from the resulting conceptual, empirical and managerial insights. Specifically, the framework provides a structured decision-support system while fostering learning and reflection among experts. The constructivist approach enabled the co-creation of knowledge through panel discussions and iterative assessments, enriching understanding and leading to more nuanced and collectively validated evaluations of both advantages and disadvantages. As a learning tool, the framework complements existing models rather than replacing them, illustrating how structured interactions between expert knowledge and quantitative techniques can generate actionable insights for decision-making.

From a theoretical standpoint, the study contributes to the emerging literature on TA-based management, agentic AI and decision support by developing and applying a constructivist analytic system capable of capturing expert knowledge, uncertainty and perceived causal interdependencies associated with TA adoption. The findings advance understanding of how AI-enabled digital representations are perceived in relation to organizational processes, decision-making and learning, while providing a structured basis for evaluating both opportunities and challenges associated with these technologies. For practitioners, the results provide structured considerations for implementing TA-based management in organizations: prioritizing automation in routine tasks, designing training programs for human-TA interaction, safeguarding privacy, mitigating algorithmic bias and ensuring human oversight in decision-making processes. For policy-making and societal impact, the study underscores the need to balance technological efficiency with ethical considerations, human well-being and the preservation of uniquely human capabilities. These insights are particularly relevant for organizations seeking to adopt TAs in sectors with high ethical, social and operational implications.

Despite its contributions, the study has several limitations. The findings rely on a single expert panel, whose experience, professional background and contextual knowledge may have shaped the results. In addition, the research was conducted within a specific organizational and cultural context, which may limit generalizability to other settings. The analytic system focuses on structured evaluation and does not explicitly account for rapidly evolving technologies or emergent societal factors beyond the expertise of the participating panel. A further limitation concerns the absence of a comparative assessment between conventional and neutrosophic DEMATEL. Although a conventional DEMATEL calculation could be performed using the original influence assessments, the present study was not designed to establish the superiority of one approach over the other. Such a conclusion would require the same expert panel to examine and discuss the results obtained from both approaches and to assess whether the differences provide a more appropriate representation of their judgments and understanding of the problem. As an additional comparative session with the expert panel is beyond the scope of the present study, the relative merits of the neutrosophic and conventional formulations cannot be established here and are therefore left for future research.

With regard to sensitivity analysis, it is important to note that the expert evaluation process incorporated an iterative assessment of alternative judgments during the facilitated sessions. Participants were able to modify assessments and immediately examine the resulting implications for the influence relationships, allowing the panel to reconsider and refine its judgments. While this interactive procedure is not equivalent to a formal *post-hoc* sensitivity analysis, it contributed to the validation and consolidation of the final causal structure. A systematic sensitivity analysis under predefined variations in expert assessments and methodological assumptions remains an important opportunity for future research.

Building on these considerations, future research should replicate the study with panels of different composition, including international and cross-sector participants, and explore alternative multicriteria techniques. In particular, future studies could apply conventional DEMATEL and neutrosophic DEMATEL in parallel using the same expert assessments and subsequently present the respective results to the same expert panel for comparative discussion and validation. Such a design would allow researchers to investigate not only differences in causal structures and rankings but also whether the neutrosophic representation provides an interpretation that experts consider more appropriate to the problem context. Future research could also undertake formal sensitivity analyses based on systematically varied expert assessments and methodological assumptions to further examine the stability of the resulting causal structures and rankings.

Overall, TA-based management remains an emerging area in management research. By providing a structured, transparent and learning-oriented framework, this study offers conceptual and practical tools for understanding and guiding the adoption of TAs, while emphasizing the importance of preserving essential human dimensions. Continued research can build on this foundation by further examining the comparative value, robustness and applicability of alternative approaches to TA-based management, ultimately supporting the responsible and effective integration of advanced technologies in organizational contexts.

CRediT authorship contribution statement

Vânia M.M. Silva: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Fernando A.F. Ferreira:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **Marina Dabić:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition. **Neuza C.M.Q.F. Ferreira:** Writing – original draft, Validation, Software, Formal analysis. **Florentin Smarandache:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis. **Afonso M.F. Ferreira:** Writing – original draft, Visualization.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors do not have permission to share data.

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