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Who decides? Positioning stakeholders in a decision-making process via network modeling and analysis: Application to regional trains decarbonization

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A B S T R A C T

Understanding and controlling stakeholder influence in public–private decision-making remains a significant challenge for public authorities. This study proposes a methodology for diagnosing, modeling, and reorganizing stakeholder contributions within complex decision-making processes. The methodology integrates five steps: stakeholder identification, stakeholder network modeling, network analysis, stakeholder clustering, and a reorganization phase that aligns stakeholder involvement with the specific objectives of each decision stage. The methodology is applied to public–private network data to reveal influence patterns, dominant stakeholders, and structural coalitions. Stakeholders are identified, and their interactions are formalized using a weighted Design Structure Matrix (DSM). Network indicators are computed to characterize interaction intensity and connectivity. Clustering algorithms are applied to identify clusters of closely interacting stakeholders, which serve as the basis for reorganizing stakeholder involvement across decision stages. We applied the methodology to the decarbonization of French regional diesel trains. Data were collected through interviews conducted with multiple regional transport authorities. The results show an intense concentration of decisional weight among industrial stakeholders and higher-level public institutions, indicating governance vulnerabilities stemming from asymmetric access to information and influence. A validation phase was conducted with a regional decision-maker (Corse), confirming the practical relevance of the proposed stakeholder reorganization and supporting its applicability to real-world decision processes. The study demonstrates that dynamically structuring stakeholder involvement can mitigate risks, enhance decision robustness, and assist public authorities in managing private-sector influence. While illustrated through a specific case study, the methodology is generalizable to any multi-actor public–private decision-making context.

1. Introduction

Understanding how industrial stakeholders influence decision-making processes is a longstanding concern in public decision-making studies. As Potters & van Winden noted, “Providing policymakers and legislators with information is often asserted to be one of the most important means by which interest groups influence the policymaking process.” (Potters and van Winden, 1992). However, while this observation highlights the centrality of information flows and informal influence mechanisms, existing modeling approaches rarely successfully capture these dynamics comprehensively. In this paper, we develop a methodology for diagnosing and modeling stakeholder networks, conducting influence analysis, and dynamically reorganizing stakeholder contributions.

This methodology is applied to the case study of the decarbonization of French regional trains, a decision context in which regional authorities act as Authorities for Organizing Transport (AOTs). They manage their train fleets and evaluate technological alternatives based on installation costs, social acceptability, and environmental performance. However, this evaluation process depends substantially on information provided by industrial stakeholders.

Aligned with the Paris Agreement, the transport sector aims for a 55% reduction in greenhouse gas emissions by 2030 compared to 1990 levels (European Climate Law, 2021). In France, 35% of the rail network

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remains non-electrified. As a result, up to 85% of the 9,137 km of low-density lines are operated by diesel trains (Mandegari et al., 2023; Ministère de la Transition écologique et solidaire, 2018; Rungskunroch et al., 2021). This reliance constitutes a significant barrier to achieving climate objectives (Ministères Aménagement du territoire Transition écologique, 2018; Zhang et al., 2018).

Mid-life maintenance of regional trains offers a strategic opportunity to transition to new propulsion technologies. A substantial portion of the regional fleet will reach mid-life between 2024 and 2031, creating a critical window to replace diesel traction. Failure to identify viable alternatives within this timeframe will require closing lines to comply with regulatory requirements.

Currently, no proven cost-efficient solutions exist to replace diesel-powered trains (European commission, 2017; Küng et al., 2018). While electrification remains the conventional alternative, it is economically unviable for low-density lines due its high infrastructure costs. Emerging technologies include battery-powered traction (Ager-Wick Ellingsen et al., 2022; Engholm & Kristoffersson, 2025; European commission, 2017), hydrogen fuel cells combined with batteries (Crönert & Minner, 2021; Haji Akhoundzadeh et al., 2021), biofuel technologies (Bernard & Prieur, 2006), and hybridization approaches (Meynerts et al., 2018).

The low maturity levels of these technologies constrain decision-makers' capacity to assess their performance characteristics and life-cycle impacts (Campanella & Ribeiro, 2011; Hunt et al., 2013). Since evaluation relies heavily on data from industrial stakeholders and operators, and decision-makers have limited budgets for experimentation, the decision-making process faces substantial information asymmetries.

Deciding on this technological swap (train decarbonization in the paper) is thus a methodological and practical challenge due to the number and diversity of decision criteria, alternatives, and stakeholders involved. It is a crucial issue, as closing low-density lines when diesel trains can no longer circulate has significant societal and economic consequences for the territory. Keeping only diesel is impossible; however, closing the lines is also undesirable.

These technical, economic, and environmental uncertainties are directly linked with the governance conditions under which such decisions are made. This paper illustrates the concept through the decarbonization of French regional trains, which serves as an example of a public–private decision-making framework. A specific decision-support process is currently lacking to help AOTs manage private stakeholder involvement, which can undermine both the efficiency and the legitimacy of the decision, even though industrial stakeholders remain essential through their investments in technology development and deployment. This process must be constructed in collaboration with public and industrial stakeholders at both local (territorial) and global levels (European Union). This process has not yet been formalized in the literature.

This research addresses the following central question:

How to reduce the risks posed by unorganized stakeholders in an asynchronous decision-making process?

This question arises from the need to understand and manage the contribution and influence of stakeholders, both public and private, across all stages of decision-making. To explore this, we identify two specific research sub-questions:

How can stakeholders and their interactions be systematically modeled, characterized, and represented along the decision-making process?

This sub-question notably focuses on developing a model to capture and analyze the structure and dynamics of stakeholder interactions, thereby facilitating a deeper understanding of the influence of various stakeholders.

How can stakeholders' network analysis and clustering be dynamically integrated into the design of the temporal allocation of stakeholders' contributions within the decision process?

Here, the aim is to explore how stakeholder identification and clustering can support, among other things, the development of a structured, adaptive, and stakeholder-sensitive decision-making methodology.

This paper aims to contribute to the research field of multi-actor public–private decision support by:

- formalizing the network of stakeholders and their interactions at different stages of the decision-making process,
- analyzing their influence on the decision-making process,
- and managing the decision process through cluster-based reorganization of their temporal allocation.
- We then offer a new structure for the decision-making process based on stakeholders' network analysis and clustering.

The structure of the paper is as follows. First, the problem statement is developed from existing literature on complex decision-making systems to highlight the research gap in Section 2. The research methodology is then described in Section 3, outlining how data are collected and how the proposed methodology is developed and tested to model stakeholder interactions and derive indicators and clustering results for reorganizing a decision-making process. The article presents the field diagnosis, detailing the interview methodology used to understand the AOTs' decision-making processes (section 4). This empirical investigation collects data necessary to model stakeholder workflows. The article then moves to the proposal building phase, using tools and methodologies supported by a literature review on stakeholder network modeling, representation, analysis, clustering, and organization (section 5). In the proposal testing section 6, we apply this methodology to model the stakeholder network through stakeholder identification and network modeling, conducting indicator and cluster analyses to organize the decision-making process. Section 7 then presents a validation phase of the proposed methodology, including its testing, to assess its practical relevance and applicability. Finally, conclusions and perspectives are drawn in section 8.

2. Related work and research question

In this section, we describe the conceptual framework of multi-stakeholder decision-making, with a particular emphasis on the importance of temporal allocation of stakeholders in the decision-making process. Failure to take this temporality into account poses several issues, including premature or late participation, excessive participation, or lobbying. Ultimately, a summary of the limitations of existing approaches will enable us to formulate the research question.

2.1. The conceptual framework of multi-stakeholder decision-making

The decision-making process begins with identifying and structuring the problem to be solved, particularly by identifying alternatives and decision criteria, followed by the process and organization that will carry it out. However, it begins with understanding the degree of complexity in the decision to be made and, therefore, everything that will result from it.

2.1.1. The complexity of the decision problem to be solved

In cases where multiple stakeholders with divergent interests must contribute to reaching a decision, complexity arises not only from the multiplicity of stakeholders but also from their interdependencies, inherent uncertainties, and often contradictory interests (Engholm & Kristoffersson, 2025; Koohathongsumrit et al., 2024).

The decision-making process examined in this study involves a complex socio-technical system, encompassing both short- and long-term considerations, regional and national perspectives, as well as economic, environmental, and societal factors (Norouzi et al., 2025). Such decisions are defined by high interdependence among diverse stakeholders, multiple and sometimes conflicting objectives, non-linear dynamics, and high uncertainty (Manzolli et al., 2025). In such environments, outcomes are difficult to predict, and small interventions can produce disproportionate or delayed effects due to feedback loops and interdependencies (Sokolova & Caballero, 2012).

2.1.2. Alternatives and decision criteria

Decision alternatives represent all possible options for responding to the identified problem. In the context of complex multi-stakeholder decisions, the generation and, above all, the assessment of alternatives cannot be carried out in isolation but require contributions from different stakeholders who bring their specific knowledge and perspectives to the table. Criteria are used to evaluate and compare the identified alternatives. The literature on multi-criteria analysis generally identifies three categories of criteria: technical criteria assess the operational feasibility and functional performance of the alternatives; economic criteria analyze costs, benefits, and financial viability; social and environmental criteria consider the impacts on populations and the ecosystem.

In a multi-stakeholder context, defining and weighting criteria is itself a matter for negotiation, as different stakeholder groups prioritize different aspects. For example, an AHP-based approach can be practical in guiding engineers in improving their decision-making processes. Still, cultural biases prevent the heterogeneous criteria from being given their fair weight, which reduces the impact of such an approach (Ma et al., 2024).

This will therefore depend on the decision-making governance, which may be collaborative or centralized around a single decision-maker (with the other stakeholders acting as participants), in which case the decision-maker will set the criteria and their weightings.

2.1.3. The stages of the decision-making process

The decision-making process can be broken down into several phases (Roy & Słowiński, 2013; Zbrishchak & Zvyagin, 2020):

(i) The structuring phase involves defining the problem, identifying the relevant stakeholders, and establishing the framework for analysis.
(ii) The evaluation phase involves analyzing alternatives according to specified criteria and gathering the necessary information to justify the decision.
(iii) The deliberation phase enables stakeholders to exchange ideas, negotiate, and seek mutually beneficial compromises.
(iv) The selection phase results in the choice of one alternative or a combination of alternatives.
(v) Finally, the implementation and monitoring phase translates the decision into concrete actions and evaluates its results.

These stages are not linear in complex contexts. Feedback loops may lead to a reconsideration of alternatives or criteria based on collective learning (Zuniga-Teran et al., 2022).

2.1.4. The organization of stakeholders in the process

No single stakeholder can fully oversee or control the system, making decision-making reliant on partial knowledge, long-term consequences, and competing viewpoints (Hasan & Crawford, 2006). As a result, traditional linear approaches such as top-down planning or single-objective optimization are inadequate. Instead, decision frameworks must be participatory and adaptive, integrating multiple perspectives and responding to emerging information (Lyons et al., 2003; Pavard & Dugdale, 2006).

The organization of stakeholders determines the quality and legitimacy of the decision-making process. The literature identifies four structural dimensions of this organization (Marle et al., 2019; Marocco & Talamo, 2022):

(i) The distribution of authority defines who has the final decision-making power. Models range from centralized (a single authority) to decentralized (multiple decision-making centers), including hybrid forms of shared governance.
(ii) Coordination mechanisms ensure consistency between the actions of different stakeholders. They can be hierarchical (command), commercial (contracts), or networked (collaborative networks).
(iii) Participation methods determine the degree of stakeholder involvement in the process. The literature distinguishes between gathering opinions, consultation (structured dialogue), and co-decision (shared power).
(iv) The temporal allocation of stakeholders to the different stages of the process.

2.2. The importance of time allocation by stakeholders in an asynchronous process and the consequences of failing to take this parameter into account

The academic literature on stakeholder participation in complex decision-making processes is extensive and widely recognizes the importance of involving relevant stakeholders. Research indicates that participation improves the legitimacy of decisions, broadens the information base, facilitates implementation, and mitigates conflict. However, the literature also shows a lack of consideration of the temporal allocation of stakeholders' contributions.

2.2.1. The limited consideration given to the temporal dimension of stakeholders' contributions

Research on stakeholders' contribution has mainly focused on three dimensions:

- who participates (identification and selection of stakeholders),
- how to participate (methods and tools for engagement),
- and why to participate (normative and instrumental justifications).

A significant gap characterizes the current state of research: the temporal dimension of participation remains undertheorized and underoperationalized. Existing work treats participation as a static attribute rather than a dynamic process unfolding over time (Hollebeek et al., 2022).

The dominant methodological frameworks do not offer clear principles for determining when the various stakeholders should be involved in the different stages of the decision-making process (Chupryna et al., 2025). Multi-level governance models describe the vertical and horizontal relationships between stakeholders, but do not explain the temporal coordination of their interventions (Schakel, 2020).

Multi-criteria analysis tools (AHP, TOPSIS, DEMATEL, etc.) incorporate stakeholder preferences but do not consider the optimal time to solicit them (Morente-Molinera et al., 2020). Participatory approaches (workshops, public consultations, citizen panels) are designed as one-off events rather than as temporally coordinated sequences (Khodyakov et al., 2015; Quimby & Beresford, 2023).

This failure to take temporality into account is also evident in the evaluation of participatory processes. Evaluation criteria focus on inclusiveness, representativeness, and influence, but rarely on the temporal adequacy between the timing of involvement and informational or decision-making needs.

The failure to systematically account for stakeholders' temporal positioning generates several dysfunctions that compromise the effectiveness and legitimacy of decision-making processes.

2.2.2. Risk 1: premature or delayed participation

When stakeholders are involved too early in the process, before the problem has been sufficiently structured or alternatives identified, their contribution is likely to be unproductive and generate frustration

(Salamanca-Cano et al., 2023). Conversely, involving stakeholders too late, when decisions have already been primarily made, reduces participation to a formal consultation with no real influence, creating a sense of being used (Aliyu et al., 2025).

The literature even documents cases where key stakeholders were consulted after the main directions had been decided, limiting their contribution to marginal adjustments and weakening the legitimacy of the final decision (Arthur et al., 2023).

2.2.3. Risk 2: excessive or insufficient presence of specific stakeholders

A lack of temporal coordination can lead to the overrepresentation of particular stakeholders at critical stages, thereby monopolizing attention and decision-making resources (Kapiriri & Razavi, 2021). This phenomenon is particularly problematic when stakeholders with significant resources (time, expertise, and mobilization capacity) can maintain a continuous presence. In contrast, others with more limited resources can only engage on an ad hoc basis (De Vente et al., 2016).

Conversely, underrepresentation at key moments can lead to essential issues or expertise being overlooked, thereby undermining the informational quality of the decision (Pagliara et al., 2025). Research shows that the absence of specific stakeholders during the initial problem-framing phases can permanently steer the process in a suboptimal direction (Scolobig & Lilliestam, 2016).

2.2.4. Risk 3: undesirable influence phenomena, such as lobbying

The lack of temporal regulation of participation creates opportunities for asymmetric and non-transparent influences (Berner-Rodoreda & Jahn, 2021). Organized interest groups with substantial resources can maintain a continuous presence with decision-makers and intervene strategically at times most favorable to their interests.

Research documents the existence of a first-mover advantage in lobbying: stakeholders who intervene early in the decision-making process can frame the issue in a manner favorable to their interests and establish privileged relationships with decision-makers (Crepaz et al., 2023). This advantage is particularly pronounced when stakeholders have significant human and financial resources at their disposal.

Lobbying mechanisms are deployed differently at various stages of the process. During the agenda-setting phase, lobbying aims to raise awareness of specific issues and dismiss others (Coen et al., 2021; Knamiller et al., 2024). During the alternative formulation phase, the aim is to guide the options under consideration. During the decision-making phase, pressure is exerted to favor a particular option (Berner-Rodoreda & Jahn, 2021).

The distinction between formal consultation and informal negotiation becomes crucial: while public consultations are documented and transparent, bilateral interactions between lobbyists and decision-makers often escape public scrutiny. This lack of transparency allows for disproportionate influence that contravenes the principles of fair participation.

2.2.5. Risk 4: disengagement

Studies on decision gates and complex project governance (National Audit Office, 2025; Samset & Volden, 2016) reveal that standard processes become bureaucratically overloaded in complex projects. Decision reviews involving hundreds of deliverables and interdependent risk factors often lead to decision paralysis, as committees are unable to meaningfully assess all inputs.

This can lead to participatory fatigue when the same stakeholders are repeatedly or continuously called upon, without their contributions yielding tangible results. This weariness gradually leads to disengagement, depriving the process of the most experienced contributions (Pagliara et al., 2025; Salamanca-Cano et al., 2023).

Research indicates that engagement quality declines when stakeholders perceive that their time is not being used effectively or that their contributions are not being considered. This deterioration particularly affects civil society representatives and citizens, who have fewer resources than institutional or economic stakeholders to maintain prolonged engagement (Arthur et al., 2023; Salamanca-Cano et al., 2023).

2.2.6. Risk 5: inconsistent and inefficient decision-making

The lack of temporal coordination produces inconsistencies between the different phases of the decision-making process (Pluchinotta et al., 2022; Zuniga-Teran et al., 2022). Objectives defined at one stage may be contradicted by the alternatives selected at a later stage, particularly when different stakeholders intervene without an overall vision (Marle et al., 2019).

For instance, Naturalistic decision-making (NDM) studies further reveal that experts tend to think within their disciplinary silos, which hinders cross-domain integration (Klein, 2017). From a governance standpoint, the diversity among decision stakeholders (engineers, financiers, politicians, and citizens) creates epistemic fragmentation that traditional top-down decision systems cannot reconcile, especially when stakeholders are not present in a synchronous mode (Brunet, 2021). The UK National Audit Office similarly reported that large public projects suffered from incompatible decision logics across agencies, each using distinct analytical frameworks at different moments, resulting in misaligned priorities and delays (National Audit Office, 2025).

The inefficiency of the process is also evident: resources are wasted on redundant or poorly targeted consultations, delays are unnecessarily prolonged, and conflicts arise due to a lack of anticipation of coordination needs (Haial et al., 2020; Zuniga-Teran et al., 2022).

2.3. Limits of existing approaches for considering the temporal allocation of interdependent stakeholders contributing to a complex decision

Decision-making in a multi-actor public–private context often involves numerous stakeholders, including public authorities, industry, and, at times, civil society. Their roles, relationships, and levels of influence vary significantly across contexts. Understanding how these stakeholders interact and influence the decision-making process is key to improving transparency, coordination, and effectiveness in such contexts. Several approaches in the literature attempt to model stakeholder involvement and influence. However, these approaches generally focus on specific dimensions of the problem (Table 1).

Methods found in the literature address only specific system components, as visible in Table 2. While stakeholder analysis for decision-making can be conducted using Cameron's approach, it would require more comprehensive data collection, which is particularly challenging given the limited availability of lobbying data. Savage's framework is constrained to evaluating how decision-makers perceive their dependence and vulnerability from industrials, whereas our analysis focuses on indicators of their influence in the decision-making process. Additionally, public-to-public relationships are absent from Potters' model. Even when combining these approaches, the existing literature falls short of providing a comprehensive analysis of our system, particularly in integrating industrial stakeholders into public decision-making.

Our approach thus must enable both the analysis of individual stakeholders and the structuring of their relationships to support the reorganization of the decision-making process. The modeling of interactions should not be limited to public stakeholders alone. Still, it must also incorporate their relationships with industrial stakeholders, whose influence and involvement are both essential and substantial in the context of train decarbonization.

2.4. Research question

This literature review highlights the wealth of work on multi-stakeholder decision-making processes in complex contexts, while pointing to a significant methodological gap concerning the temporal dimension of participation. In the specific case of regional rail traction technology choices, this gap is particularly problematic given the multiplicity of stakeholders involved (local, national, European, public,

Table 1
Approaches for decision-making stakeholders influence modeling in the literature.

N°	Approach	Description	Objective (limit/involve)	Reference
1	Participatory approach and local governance	Involves public, private, and civil society stakeholders in decision-making through participatory frameworks.	Limited to organizing stakeholders' interventions in the decision-making process, particularly public stakeholders. Objective for better distribution of responsibilities and engagement.	(Guillemot, 2012)
2	Graphical modeling and stakeholder zoning	Uses spatial zoning and graphical modeling to organize stakeholder interventions based on geographic and social criteria.	Limited to public stakeholders and their proper involvement in spatial decisions.	(Bonin et al., 2001)
3	Organizational impact assessment for change	Study a stakeholder's influence in a network of stakeholders based on their actions.	Identify the full weight of a stakeholder within a network by analyzing all their actions, even indirect flows.Limited to one stakeholder.	(Cameron et al., 2011)
4	Strategies for assessing And managing OrganizationalStakeholders	Reorganize stakeholders based on the threat they pose.	Unable to reinforce positive relationships. No clustering analysis.	(Savage et al., 1991)
5	Lobbying and asymmetric information	Modeling industrial willingness to lobby.	Limited to industrials-decision-makers interactions.	(Potters and van Winden, 1992)
6	Business stakeholders modeling	Model workflows in a business context.	Limited to industrial interactions.	(Tsvetkova et al., 2019)

Table 2
Parts of our system represented in the literature.

Literature from Table 1 numeration	Stakeholders' analysis	Stakeholders' relationship organization	Decision process organization
Public stakeholders	2–3-5	1–2-4	1–2
Industry stakeholders	3–5-6	4	

private, and associations) and their complex interdependencies.

The consequences of this lack of temporal coordination manifest as inadequate participation (too early, too late, too much, or too little), asymmetrical and undesirable influences (opportunistic lobbying), and, ultimately, a deterioration in the quality and legitimacy of decisions. These dysfunctions necessitate the development of methodological frameworks and operational tools to coordinate stakeholder participation timing in complex decision-making processes.

This diagnostic reveals a clear research gap: the lack of a framework capable of capturing the multi-level, evolving influence of public and private stakeholders across all stages of the decision-making process.

This enables us to formulate our research question, already presented in the Introduction:

- How can stakeholders and their interactions be systematically modeled, characterized, and represented along the decision-making process?
- How can stakeholders and their interactions be systematically modeled, characterized, and represented along the decision-making process?
- How can stakeholders' network analysis and clustering be dynamically integrated into the design of the temporal allocation of stakeholders' contributions within the decision process?

3. Research methodology

This section presents the research methodology adopted to investigate and structure the multi-actor decision-making process involved. The level of complexity in the context of decarbonization decisions for regional railway systems is very high, due to the simultaneous presence of short- and long-term considerations, as well as technological, economic, environmental, and societal objectives. Additionally, public decisions involve contributions from both public and private stakeholders, further complicating the process.

Therefore, a methodology was required that could describe empirical practices, represent current stakeholders' contributions and interactions, and simultaneously support the development of a prescriptive decision-aiding tool for better temporal allocation of stakeholders' contributions.

Following the classification of research method groups proposed by Mäkinen (Mäkinen, 1999), this study adopts a constructivist research approach (see Table 3), to describe the current situation and provide prescriptive solutions to improve it. This approach emphasizes the co-construction of knowledge between the researcher and the empirical context under investigation.

The research process involves conceptual reflection and empirical engagement. Such an approach is particularly suitable for exploring complex systems where the aim is to build contextually grounded insights. Our three-phase approach is outlined below.

3.1. An interview-based field diagnosis to capture current practices and problems

Interviews aim to elicit detailed insights into stakeholder dynamics and decision-making practices related to train decarbonization. The interviews enabled the identification of key stakeholders and stages within the decision-making process. They also allowed the identification of different operational problems for the decision-maker.

3.2. Building conceptual proposals

We model actor-to-actor interactions in a decision-making context. The focus is on modeling interactions between public and private stakeholders, developing metrics of their influence, and organizing the decision-making process, particularly regarding their temporal allocation across the process stages.

Based on interview data and literature, we develop a conceptual methodology to model and then analyze the network of stakeholders involved in regional train decarbonization. This model enables the analysis of the diversity of stakeholders, the nature of their relationships, and the dynamics of their influence throughout the decision-making process. Then, clusters are proposed to group stakeholders depending on their interactions. Finally, the temporal allocation of their contributions is reshuffled based on this clustering and network analysis. It enables a more transparent, structured decision-making process by

Table 3
The five groups of research methodologies according to Mäkinen, adapted from (Marle, 2020).

	Theoretical	Empirical
Descriptive	Conceptual approach	Nomothetic approach
Normative	Decision-oriented approach	Action-analysis and constructivist approaches

improving stakeholder contributions and limiting potential risks, such as inadequate, premature, or delayed participation.

3.3. Testing and validating

The conceptual methodology was tested using empirical data collected during interviews. This was thus a generic case, not based on a specific region. It was applied to structure the stakeholder network, analyze influence patterns, and assign stakeholders to relevant stages of the decision-making process. Through this application, the model demonstrated its capacity to highlight both expected relationships, such as strong interdependencies among public authorities, and more surprising configurations, including the central role of specific private stakeholders. These results reinforced the model's operational relevance by reshuffling stakeholders' contributions over time and limiting undesirable phenomena, such as lobbying.

Results have been presented to the region of “Corse”. They were able to formulate a positive opinion about the relevance of the proposals and the feasibility of their implementation. This initial validation paves the way for application to a real decision-making process when the next train traction technological swap takes place.

4. Field diagnosis: capturing current operational practices and problems through interviews

Our approach to formulating the problem has been to conduct interviews with various stakeholders involved in the decision-making process.

That enabled outputs to be captured and formalized:

- The decision-making process stages (Fig. 1)
- The required and involved public and industrial stakeholders at the different stages of the decision-making process (Table 4)
- The operational problems

To the best of our knowledge, this decision-making process had not been previously explicitly described in the literature in the form presented here.

Data were collected through interviews with representatives from different AOTs. The interview objectives, methodology, and details about the interviewees are provided in Section 10.1 of the supplementary materials, along with the interview guide.

The internal organization of the AOTs, detailing the respective roles, responsibilities, and hierarchical relationships between departments, is provided in Section 10.2 of the supplementary materials. Although not directly used in the network analysis, it illustrates the organizational complexity of each AOT and the complex influence network that it encompasses. It is considered a single aggregated decision-maker in the present study, as this complexity is not relevant to the network analysis.

4.1. Describing the decision-making process stages

Following the decision-making stages identified in Section 2.1.3, the interview process allowed us to identify the various stages of the train decarbonization decision-making process and its stakeholders. While political considerations constrain the sequence of decision stages and therefore remain unchanged, the stakeholder configuration within each stage can be reorganized nonetheless. Although these stages are complementary, some interviews did not identify all of them. We reconstructed a representation of the whole decision process from the stages detailed in this paragraph and represented in Table 12 in the supplementary materials section 10.3. Some regions may skip certain stages, and other representations of the same decision process may also be valid. The table illustrates the structured but heterogeneous nature of the process, revealing how different regions have progressed at varying speeds and depths. While a broadly shared sequence of decision stages exists across regions, their actual implementation varies significantly depending on local institutional dynamics, stakeholder engagement, and data availability. Several interviewees explicitly mentioned specific decision stages, while others only implied their existence during the interviews. Some have initiated advanced stages, such as simulations or environmental assessments, while others remain in preliminary data collection or criteria definition phases. This uneven progress underlines the fragmented maturity of regional decision processes. It recognizes the need for an adaptable decision support methodology to guide regions toward greater decision coherence and consistency.

Table 4
Stakeholders' current intervention in the decision stages (as is).

Stage	Stakeholders involved	Stakeholders required
1. Data evaluation	**Industrials**	Railway industrials **DGITM**
2. Development of criteria	**Railway industrials**	**French government**
3. Performance simulation	Railway industrials	Railway industrials
4. Preliminary Technological Comparison		**Railway industrials** **DGITM**
5. Environmental impact assessment	Industrials	**Industrials** **Public authorities** **Environmental experts**
6. Cost analysis	Industrials	Industrials **Public authorities**
7. Technical and Political Validation		**Public authorities**

The first stage is data evaluation. Once the need for a decision is established for the region, they will evaluate available data, identify potential needs for this decision, and consider relevant criteria. The stakeholders involved in this stage vary by region, with the potential involvement of numerous industrial and consultancy stakeholders, as well as limitations within the railway industry. Identifying possible alternatives for this choice is part of the initial evaluation and collection process. The second stage is developing criteria for selecting and eliminating technological alternatives. This stage varies significantly across regions and can involve all identified stakeholders, including consultants, industrial stakeholders, and public authorities. Although this stage does not directly involve industrial stakeholders, it is influenced by them, either directly or through the data provided. This stage marks the beginning of an objective to achieve political validation of the decision

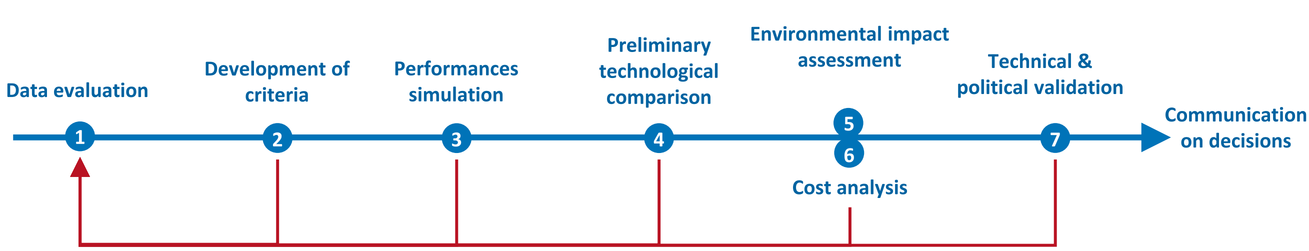

Fig. 1. Decision stages representation.

by decision-makers, which is defendable in the face of opposition.

The performance simulation of upcoming technologies is developed in collaboration with the railway industries, as railway data is managed by rolling stock manufacturers and railway network operators. It explains the high degree of dependence of the decision-making process on the railway industry. The railway industry is closely connected to decision-makers, as it holds most of the railway data crucial to its evaluation. That explains their importance for data evaluation. Then, a preliminary technological comparison, based on performance simulation results, the identified criteria, and the available initial data, identifies technologies eligible for the territory for further comparison. This stage is the primary responsibility of the regional technical services. To select among those alternatives, the multiple-criteria analysis further develops this comparison. A more thorough analysis of the technologies and criteria is created in this process, encompassing both environmental and financial aspects. This comparison relies on substantial data and involves all identified stakeholders, as they have an influence and/or an interest in the comparison configuration. If the comparison allows technical and political validation by the decision-makers, this decision is communicated in a plenary session. However, if no decision is made, the decision process must be renewed.

This decision-making process is not strictly linear. It may conclude at any stage, resulting in the selection of a technology, the rejection of all current options, or the failure to identify a preferable alternative. In such cases, the decision-making process may be reinitiated to allow for a more comprehensive analysis or to incorporate new, more precise information about existing or emerging technologies, as represented by the red arrows in Fig. 1.

Regions such as “Bourgogne-Franche-Comté”, “Grand-Est”, and “Nouvelle-Aquitaine” have already reached preliminary conclusions from a complete decision-making process, identifying promising technologies suitable for experimentation in their territories. These early outcomes have led to initial procurement efforts to conduct pilot projects and gather additional data. Conversely, some regions have yet to initiate the decision-making process. For instance, Regions such as “Bretagne” await the outcomes of experiments conducted by other regions to inform their decision-making process. Different regions, such as “Corse” (Corsica), must wait for a decision on national subsidies before they can begin the decision-making process.

Depending on specific needs and regional context diversity, the objective may be either to select a single alternative or to define a portfolio of complementary solutions that together support the decarbonization of the regional rail fleet.

4.2. Stakeholders involved and required for each stage of the decision-making process

Table 4 maps the current and required stakeholder involvement across the key stages of the regional decision-making process. It distinguishes between the stakeholders already participating in each stage and those whose presence is required to ensure a more comprehensive and balanced approach. Differences between the present and needed stakeholders are shown in bold.

Table 4 highlights a gap between the stakeholders involved and those needed by the decision-makers. While railway industry stakeholders are required at some decision stages, their involvement is not aligned with decision-makers’ needs. Moreover, public authorities remain absent from the decision-making stages. Section 2.2 details the risks associated with ill-timed stakeholder intervention, including premature or delayed participation, unbalanced stakeholder representation, undesirable influence phenomena such as lobbying, stakeholder disengagement, and, ultimately, inconsistent and inefficient decision-making. Moreover, in the context of French regional decision-making, ensuring the appropriate engagement of necessary stakeholders is essential to securing legitimacy, technical depth, and policy alignment.

4.3. Operational problems detected during the interview

Public stakeholders, industrial stakeholders, and consultancy organizations play a crucial role in informing decision-making. They provide essential data, expertise, and perspectives indispensable for decision-makers facing the complex task of comparing technological alternatives for train decarbonization. Their input helps reduce uncertainty.

However, these contributors also carry their own constraints and biases: public stakeholders operate under electoral pressures and agendas, industries may defend vested interests in promoting solutions that are oriented, and all stakeholders, regardless of their role, face resource constraints that may limit the scope and depth of their contributions. If their involvement in the decision-making process is left unregulated, it can distort power dynamics, undermining the process. Information asymmetries, lobbying, or strategic data framing may undermine the neutrality, credibility, and, ultimately, the legitimacy of the decisions.

Conversely, excluding these stakeholders altogether is not a viable option. Their absence would deprive decision-makers of critical information, potentially weakening the robustness of the decision. Recognizing this tension, decision-makers have already attempted to engage independent consultancy organizations intended to act as neutral third parties. These stakeholders are tasked with mitigating biases, aggregating information, and providing more objective analyses to guide political choices. However, this approach is not without limitations. Interviews reveal that complaints have been made regarding the quality of consultancy work, rendering its results unexploitable while taking a toll on decision-makers’ resources.

In this context, the analysis of the interviews highlights a central issue**:**

The operational challenge lies in finding a balance between enabling stakeholder contributions to enrich decision-making without compromising the autonomy, rationality, and integrity of final decisions. Based on this challenge and the risks identified in the literature in Section 2.2, we formulate our methodological proposal in the following section.

5. Proposal building: Positioning stakeholders in the decision-making process via network modeling, analysis, and clustering

We propose in this section a tailored methodology based on stakeholder network modeling, analysis, and clustering, enabling the evaluation and management of stakeholders’ temporal allocation and thereby influencing decision-making. This methodology supports decision-making by positioning stakeholders and limiting their influence accordingly.

The proposal can be summarized as follows:

- Step 1: Identification of relevant public and private stakeholders involved in the decision process,
- Step 2: Modeling of the stakeholders’ network based on identification and assessment of their interactions,
- Step 3: Analysis of the network's structure through indicators to highlight the potential influence of specific stakeholders due to their place in the network,
- Step 4: Clustering stakeholders based on their interactions and their place in the network,
- Step 5: Prescribe a reorganization of stakeholders’ contributions along the decision stages, ensuring that at each stage, alignment is maintained with its specific objectives.

The proposed five-step methodology responds to the Research question.

Steps 1 and 2 answer the first sub-question: How can stakeholders and their interactions be systematically modeled, characterized, and represented along the decision-making process?

Steps 3 to 5 answer the second sub-question: How can stakeholders' network analysis and clustering be dynamically integrated into the design of the temporal allocation of stakeholders' contributions within the decision process?

Step 3 assesses how to characterize these interactions by providing a quantitative indicator analysis of stakeholder influence and network structure. Step 4 integrates clustering into the methodology by defining and refining stakeholder clusters in line with decision-makers' objectives. Step 5 recommends how to position stakeholders' contributions throughout the decision-making process.

5.1. Step 1: stakeholder identification

Gaziulusoy's classification method allows for mapping the stakeholders of a socio-technical system (Gaziulusoy & Brezet, 2015). This matrix sorts stakeholders on the x-axis by size and groups them on the y-axis into four categories: institutional, social/cultural, organizational, and technological, as illustrated in Table 5. This methodology provides a good representation of a system and serves as a checklist to ensure all stakeholders are identified.

This checklist is particularly relevant for identifying small stakeholders on the socio-technical scale, which can be more numerous and typically characterized by a more fragmented distribution of interactions.

5.2. Step 2: Stakeholder network modeling

This subsection first introduces the principle for identifying and quantifying interactions between stakeholders. Next, we present the approach for modeling these interactions in a stakeholder network as a matrix.

5.2.1. Quantitative assessment of stakeholder interactions

In our context, stakeholders are the key entities or groups involved in the system and contribute to, or at least influence, the decision. Tsvetkova and Ouarda analyzed workflow interdependence within and around a project embedded in a business. The authors' data were collected through interviews, observations, and the examination of archival sources to develop a project analysis framework of workflows within a business ecosystem (Tsvetkova & Ouarda, 2019). This analysis uncovered four workflow types, detailed in Table 6.

We regrouped our workflows by the types in Tsvetkova's Table 6. We associate weight with each workflow type, following a similar approach to Cameron's (Cameron et al., 2011):

- Pooled interdependence is set as the reference weight for workflow types at 1.
- Reciprocal contentious interdependence imposes a high constraint on the system, as these stakeholders primarily develop different or opposing ways to influence the decision. The weight is set to three (3) times the pooled interdependence.
- Sequential interdependence has an intermediary impact, with a weight of 2.
- Compatible reciprocal interdependence encourages workflow resolution; its weight is at −1.

5.2.2. Stakeholder interactions mapping

Various graphical approaches can be used to emphasize stakeholders as nodes and interactions as edges (Fassin, 2008). A first-orbitals method, centered on a specific stakeholder, has been used to build a simplified graphical representation of stakeholder relationships in train decarbonization decision-making (see Fig. 2). However, this mapping lacked several key interactions, limiting the analytical interpretation of stakeholder dynamics.

Table 6
Workflow interdependencies and mechanisms for their coordination and governance (Tsvetkova et al., 2019).

Name		Description
Pooled Interdependence		The simplest type of workflow involves "pooled" interdependence, in which workers accomplish a set of activities that are all necessary to achieve the desired system-level outcome. However, there are no technical or timing interdependencies between tasks.
Sequential Interdependence		If a given task that already has pooled interdependence with all other functions in the project faces the additional constraint that it cannot be initiated until one or more prerequisite tasks have been partially or fully completed, the two or more involved tasks exhibit "sequential" interdependence as well as pooled interdependence.
Reciprocal Interdependence		The third type of workflow involves "reciprocal" interdependence between two or more subtasks.
	Compatible-reciprocal	"Compatible-reciprocal" interdependence requires mutual adjustment to achieve a spatial or functional fit between the task outputs of the interdependent workers; however, achieving this fit does not entail conflicting subgoals for the involved stakeholders.
	Contentious-reciprocal	In contrast, "Contentious-reciprocal" interdependence also requires mutual adjustment to achieve a spatial or functional fit between the outputs of the interdependent workers' tasks; however, achieving alignment now invokes conflict between one or more of the subgoals held by each worker—i.e., a given choice of the output that is more desirable to one is less desirable to the other and vice versa.

Table 5
Co-evolutionary dynamics within the socio-technical system adapted from (Gaziulusoy & Brezet, 2015).

		Scale of the socio-technical system element		
		Small	Medium	Large
Type of the Socio-technical System Element	Institutional	Science and technology policy Environmental policy Science/ research Policy Etc.	National Law/Constitution Policy Development Strategies/Plans Etc.	International Laws/Agreements/ Treaties Basic Science Economic System Etc.
	Social/ Cultural	User/consumer Personal values/ beliefs/ethics Etc.	Local/Regional Market Ethnic/National Culture Community values/ beliefs/ethics Etc.	Global Market Societal norms/values/ beliefs/ethics Etc.
	Organisational	Individual Company (SME) Local NGOs Etc.	Community Company (Large/Multi-National) Sector International NGOs Small Trade Unions/ Partnerships Etc.	Society Industry Large Trade Unions/ Partnerships Etc.
	Technological	Product Service Product-service System Etc.	Technological Regime Etc.	Infrastructure Technology System Etc.

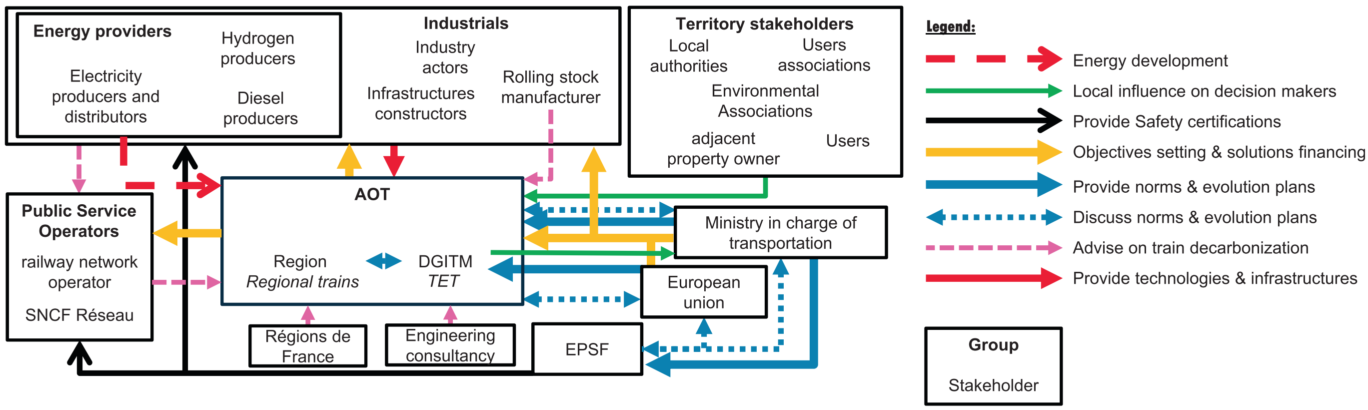

Fig. 2. Stakeholders network representation.

A more comprehensive spaghetti graph has been created to visually map all relationships and interactions among stakeholders within a system. While offering a transparent and holistic view of stakeholder relationship structures, it becomes visually overwhelming as system complexity increases (see Fig. 7b). When graphical representation reaches its limit, matrix representation becomes more suitable for readability and analysis (Yassine, 2004).

Initially developed for technical system decomposition, the DSM has seen increasing use across engineering design, management, and systems engineering over the past decade, in various contexts, including activity planning, product component management, project organization, risk assessment, and deliverables (Browning, 2016). Several studies have demonstrated its relevance for decision support. Feng (Feng et al., 2010) showed that DSM-based representations significantly enhance decision-making efficiency, while Durango (Durango et al., 2022) highlighted that DSM tools simplify system complexity and improve decision process transparency. The DSM appears adaptable for modeling stakeholders involved in regional railway decarbonization, enabling a systematic analysis of interactions, network metrics, and decision-making clusters.

A DSM uses a matrix structure to represent relations and dependencies among objects (Steward, 1981). Introduced for task-based system modeling, DSM has expanded its application beyond initial planning issues to model relationships among various entities, such as product components (Eppinger & Browning, 2012), project organization (Worren et al., 2017), risks (Fang et al., 2010; Marle, 2010), and deliverables (Jaber et al., 2018). DSMs can be binary, indicating the presence of dependencies, or numerical, quantifying their strength. DSMs can also be oriented from rows to columns or vice versa, or symmetrically around their diagonal axis.

A DSM is used to represent relationships between stakeholders (Yassine, 2004). To describe every possible relationship among these stakeholders, we chose a bidirectional approach: each stakeholder is represented once on the x-axis and once on the y-axis. At the intersection between two stakeholders on the matrix, we can read their interactions in a specific direction. Interactions must be read from lines to columns, as is often done in the literature, following the Incidence Rule (Browning, 2016). In our use of the DSM, the stakeholders on the abscissa are the initiators of the interaction, and those on the ordinate are the recipients. This methodology is better suited for representing complex systems than a diagram (Fassin, 2008). This paper is a classic example of initially representing the system graphically (see Fig. 2) until it becomes too complex to allow further data collection (see Fig. 7), prompting us to switch to a matrix representation and analysis, as shown in the DSM (see Table 7).

Table 7
DSM of train decarbonization stakeholders.

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18
A1		4	4	3	6	3	3	3	3	3	4	4	3	2	2	3	3	3
A2	4		3	3	1	3	3	3	3	3	4	5				1	3	1
A3	4	1		3	1	3	3	3	3	3	1	1				1	3	1
A4	4	1	1		1	3	3	3	3	3	1	1				1	3	1
A5	3	3	3	3		3	3	3	3	3	3	3	3	2	2	3		-1
A6	3	3	3	3	3		3				1	1	3	3	2			3
A7	3	3	3	3	3						1	1	3	3	2			-1
A8	3	3	3	3		3					1		3	3	2			-1
A9	3	3	3	3	3	1	1	1		1	1		3	2	2			-1
A10	3	3	3	3	3						1	1	3	3	2			-1
A11	3	3	3	3	3	3	3	3	3	3		2		2	2			2
A12	3				3	3	3	3	3	3	3		3	2	2	3		
A13	-1	1	1	1	1	3	3	3	3	3	4	4						
A14	2	2			2		2	2	2	2	2	2			2			
A15	2																	
A16	3	3	3	3	3			3	3		2							
A17						3						3				3		
A18	3	3	3	1		3	3	3	3	3			1				3	

5.3. Step 3: The network theory-based analysis

This analysis aims to capture the network's key features and its most significant stakeholders. It relies on three types of analysis: topological, weight, and connectivity.

5.3.1. Indicators analysis

A network is a graph, represented by its adjacency matrix $g \in \mathbb{N}^{n \times n}$. We consider a weighted network with n nodes, indexed by $i \in \{1 \ldots n\}$. $g_{ij} \neq 0$ indicates the existence of an edge between nodes i and j with g_{ij} the edge's weight.

Network workflow theory is based on various indicators attached to graph nodes, edges, or subgraphs (such as loops and cliques). We have drawn on elements used in other contexts, such as centrality (Borgatti, 2005), reachability (Sinha and De Weck, 2009), betweenness (Perera et al., 2018), and closeness (Wang & Wang, 2014).

We consider here several widespread indicators:

- The in(out)-degree: Nodes with high in(out)-degree centrality, Ω_i^+ (Ω_i^-), receive (send) many direct connections from (to) other nodes in the network. Without considering their weights, the number of edges indicates the number of connections this node must manage.
- The weighted in- or out-degree: Counting the total weights of in- or out-relationships, φ_i^+ & φ_i^-, gives another information about the amount of information or strength of influence (Opsahl et al., 2010).

$$\varphi_i^+ = \sum\nolimits_{j=1}^{n} g_{ij} \tag{1}$$

$$\varphi_i^- = \sum\nolimits_{j=1}^{n} g_{ji} \tag{2}$$

- The total node weight is the sum of the weighted in- and out-degrees (Borgatti, 2005).
- The total node normalized weight φ_i is similar, but the weighted in- and out-degree sums are normalized (Cameron et al., 2011).

$$\varphi_i = \frac{\varphi_i^+ + \varphi_i^-}{2\sum_{i=1}^{n} \varphi_i^+} \tag{3}$$

- The Normalized degree centrality of a node i Ω_i is the degree sum divided by the maximum possible degree, expressed as a percentage. In social networks, individuals with a high degree of centrality often have many friends or followers, indicating a high level of social influence. In transportation networks, nodes with a high degree of centrality may represent major intersections or transportation hubs (Barabási, 2017).

$$\Omega_i = \frac{\Omega_i^+}{\max(\Omega_i^+)} + \frac{\Omega_i^-}{\max(\Omega_i^-)} \tag{4}$$

- Normalized betweenness centrality measures the importance of a node in connecting other nodes in the network. It considers all geodesics between two nodes, j and k (different from i), and all possible combinations that pass through i (Bloch et al., 2023; Freeman, 1978).
- Normalized Closeness centrality $C_c(i)$ measures a node's i distance ρ(i) from all other nodes j. This measure has been inverted to grow with the node's centrality and normalized to facilitate its interpretation (Bloch et al., 2023; Sabidussi, 1966).

$$C_c(i) = \frac{n-1}{\sum_{j \neq i}^{n} \rho(i,j)} \tag{5}$$

- Harmonic Centrality: The sum of the reciprocals of the shortest path distances from a node to all other nodes in the network. Nodes with high harmonic centrality can quickly reach many different nodes in the network, either directly or indirectly. Individuals with high harmonic centrality may be more likely to contract or spread disease in disease transmission networks. In social networks, individuals with high harmonic centrality may have diverse social ties, which can influence the flow of information or resources in the network (Rochat, 2009).

$$C_h(i) = \frac{1}{n-1} \sum\nolimits_{j \neq i}^{n} \frac{1}{\rho(i,j)} \tag{6}$$

5.3.2. Weight analysis

The total node-normalized weight φ_i of a stakeholder i is used to assess and compare the relative weight of each stakeholder within the decision-making process. This indicator can be analyzed at the individual level or aggregated by stakeholder groups to determine the relative influence of different stakeholder categories. Reporting these values in pie charts or tables enables a visual comparison of stakeholder weights.

Cameron used this approach to evaluate NASA's societal impact (Cameron et al., 2011). Cameron first identified NASA's surrogate economic stakeholders. Then, he identified their workflows and regrouped them into categories. A notation system was developed to assign a weight to each category in the decision process. Once weighted, he could sum up each stakeholder's workflow notations to evaluate the impacted stakeholders by NASA. We note that the author arbitrarily decides the relationship's weight.

5.3.3. Connectivity analysis

Connectivity within the stakeholder network is analyzed using normalized degree centrality, normalized betweenness centrality, normalized closeness centrality, and harmonic centrality. These indicators are computed for each stakeholder based on the DSM-derived interaction network. The resulting values are used to assess and compare stakeholders' structural positions in terms of direct connectivity, intermediary role, and proximity to the rest of the network. The indicators are analyzed individually to identify structurally central stakeholders and jointly to highlight complementary roles in network connectivity. The results are reported in tables and graphs to support the interpretation of stakeholders' structural influence and coordination capacity within the decision-making process. Grouping pie charts and tables may also be helpful for their analysis.

5.4. Step 4: interaction-based clustering of stakeholder network

To reorganize stakeholder involvement, their interconnections must first be analyzed to ensure that strongly connected stakeholders remain together. Clustering algorithms are applied to the network model to identify stakeholder clusters. These clusters are then refined based on network indicator analysis and decision-makers' needs. Finally, the sensitivity of the resulting clusters is assessed to validate their robustness.

5.4.1. Stakeholders' network clustering

In complex networks where numerous links can complicate representation and management, clustering helps group similar or closely related elements, simplifying network analysis and understanding. This approach not only clarifies the network's structure and dynamics but also helps identify strategic points for intervention or further analysis. In previous work, clustering has been used to organize interdependent elements into groups with strong interactions (Ventroux et al., 2018). It has been developed in different contexts, forming clusters of various objects such as activities, stakeholders, and complexity-induced project failure factors (Rodríguez Montequín et al., 2018), deliverables (Jaber et al., 2018), components of a product (Thebeau, 2001), project scheduling problem-related behaviors and decisions (Rudeli et al., 2018), project risks (Marle & Vidal, 2013), and project decisions (Campagna et al., 2020). This method offers several advantages in decision-making and management. For instance, a clustering approach to building a group of stakeholders engaged in numerous collaborative decisions can lead to coordinated and potentially more collective choices.

Among the prominent algorithms, the Newman-Girvan and Leiden algorithms have gained significant attention for their ability to identify community structures in networks and graphs (Giannikas et al., 2022). The Newman-Girvan algorithm is a hierarchical clustering method that aims to maximize the modularity of a network (Riva et al., 2023). It iteratively removes edges with the highest betweenness centrality, effectively separating communities within the network. The Leiden algorithm offers an efficient and scalable approach to community detection, moving nodes between communities to optimize the modularity metric (Li et al., 2023).

5.4.2. Post-treatment reorganization of stakeholder clusters

To further enhance the relevance of the clusters, a post-processing phase is conducted based on the topological indicator analysis. Network metrics are used to refine the initial clustering structure by identifying dominant, bridging, and connected stakeholders and subgroups. This refinement process enables both the consolidation of coherent clusters and the introduction of additional clusters. As a result, the finalized clustering simultaneously captures the topology of the stakeholder network and its role within the decision framework. Aligning stakeholder involvement with the appropriate decision step helps prevent risks such as premature or delayed participation, unbalanced stakeholder representation, undesirable influence, including lobbying, stakeholder disengagement, and, ultimately, inconsistent and inefficient decision-making.

5.4.3. Sensitivity analysis of atypical interaction values

To ensure robust clustering and network-based analysis, a systematic sensitivity analysis is used to address atypical interaction values. This procedure combines quantitative verification with qualitative interpretation. First, the impact of such values on clustering stability is assessed through sensitivity checks. Second, their practical meaning within stakeholder communication circuits is examined to adjust their position in the clusters. These adjustments are evaluated through network indicators analysis and governance-based reasoning linked to stakeholders' roles. This approach ensures that the methodology remains transferable, adaptable to local contexts, and robust to structural ambiguities in stakeholder interaction data.

5.5. Step 5: Temporal allocation of stakeholder contribution

The clusters identified and refined in the previous step are leveraged to reorganize stakeholder involvement throughout the successive stages of the decision-making process. Rather than modifying the process structure itself, this step focuses on regulating who intervenes, when, and under which configuration of interactions. Each decision stage is associated with one or more clusters based on its objectives. This dynamic allocation enables the maintenance of stakeholder participation that remains relevant, proportionate, and temporally consistent with the nature of the decisions being addressed. By structuring stakeholder intervention in this way, the approach aims to prevent the risks identified in section 2.2, including ill-timed participation, excessive or insufficient presence of specific stakeholders, and undesirable influence phenomena such as lobbying. As a result, the cluster-based reorganization provides an operational mechanism to preserve the autonomy, rationality, and integrity of the decision-making process while maintaining the benefits of multi-actor participation in a public–private governance context.

For each decision stage, identify the stakeholders who should be involved. For example, in the context of train decarbonization, these requirements are specified in Table 2. Stakeholder participation is organized by mobilizing the smallest cluster to which each required stakeholder belongs, ensuring that only the relevant clusters intervene at each stage of the decision-making process.

6. Proposal testing: application to the 18 stakeholders involved in traction technology decisions

This phase tests whether the tools previously introduced can effectively structure and clarify who contributes, when, and how within the decision process. It operationalizes the methodology through stakeholder network modeling and analysis based on field data. Our proposal was tested with real stakeholders involved in selecting a technology for train traction systems. However, the data were generic (collected from interviews) and not specific to a particular region. A post-test validation has been carried out by interviewing a specific region, “Corse”, regarding the relevance and feasibility of implementation (presented in section 7).

We followed the steps described in Section 5.

6.1. Step 1: stakeholder identification

Thanks to Gaziulusoy's matrix (Gaziulusoy & Brezet, 2015), we collected interview data from all stakeholders involved in the decision-making process.

6.1.1. Public institutions

French regions (A1) serve as AOT within their respective territories. However, for inter-regional low-speed trains, referred to as “Trains d'Équilibre du Territoire” (TET for Regional Express Trains), the authority shifts to the Directorate-General for Infrastructure, Transport and Mobility (DGITM) (A13). The DGITM operates under the Ministry of Transportation (A2), part of the French government (A3). Each of these public bodies operates with distinct mandates and constraints and is therefore modeled separately in our analysis. The European Union (A4) is considered the highest level of authority in this framework. Below the regional level, local authorities, such as departments and municipalities, also play a role, alongside other territorial stakeholders (associations), grouped under “other territorial stakeholders” (A17). In addition, the French Public Railway Safety Authority (EPSF) (A16) is responsible for issuing safety certifications for rolling stock and railway infrastructure.

6.1.2. Consultancy stakeholders

The “Régions de France” association (A15), created by the French regions, acts as a coordination and consultancy body to identify synergies between regions and optimize inter-regional investment strategies. Furthermore, regions may contract engineering consultancy firms (A14) to validate existing information, build new technical expertise, or act as a buffer between industrial stakeholders to collect data while avoiding lobbying efforts.

6.1.3. Industrial stakeholders

SNCF Réseau (A11) is the public infrastructure manager, responsible for the construction, maintenance, and financial management of the railway network, including energy infrastructure. It collects access fees from railway operators (A12), such as SNCF, Trenitalia, Deutsche Bahn, and others, reflecting the sector's liberalization under European law (Pernice & Debyser, 2023). Rolling stock manufacturers (A5) produce and maintain the medium-speed trains used in this context, including retrofitting existing trains. Infrastructure constructors (A8) handle construction and maintenance tasks not covered by SNCF Réseau. Electricity providers (A6) supply power to the network, while hydrogen (A7) and diesel (A10) producers are responsible for the production, transport, and storage of alternative and traditional fuels. Lastly, we group various additional companies mentioned in interviews, such as battery manufacturers, under the label “industry stakeholders” (A9), as they were referenced by stakeholders but not considered first-level stakeholders.

6.2. Step 2: Stakeholder network modeling

An orbital representation of the stakeholders and their relationships within the decision process, built and validated with interviewees from the regions by Volant et al., is shown in Fig. 2 (Volant et al., 2024). It adopts the section 5.2.2 approach of centering the diagram around the final decision-maker. The relationships among the stakeholders involved in the decision-making process, whether directly or indirectly, are also represented, including the interviewees' feedback. This data-gathering method ensures the representation of all stakeholders through the interviewees' input. However, the interview process enables us to identify further and more detailed workflows that are not apparent in this initial representation. However, given the already high complexity, a more complete representation is not readable, as shown in the spaghetti graph below in our analysis (see Fig. 7). Therefore, a more complete modeling approach was necessary. We employed a DSM approach to ensure that we captured all the workflows and analyzed them.

The DSM aggregates the different relationships between two stakeholders and assigns weights to each interaction. Once the DSM workflows have been converted to weights, we obtain a non-binary DSM (Table 7) that serves as a basis for further network analysis.

The weighted DSM representation in Table 7 highlights the multitude of interdependencies between stakeholders. The first insight is the high percentage of high-weight links going to the regions. Moreover, on a total of 306 potential values, there is only one "6″ (corresponding to two relationships of value 3), one "5", and ten "4" (corresponding to 3 + 1). The value with the highest percentage of occurrences is "3" (contentious reciprocal, with 124 times or 41% of total cells), followed by "0", with 102 occurrences and 33% of cells. Low values are represented by lower percentages, with six occurrences of "-1" (2%), 34 occurrences of "1" (11%), and 28 occurrences of "2" (9%). After this initial fundamental analysis, three alternative types of analysis are performed to extract information from the raw DSM: a relative influence analysis regarding edge weights, a network theory-based topological analysis, and an interdependency-based clustering.

6.3. Step 3: The network theory-based analysis

Based on the structure introduced in Section 5.3, three indicator types are calculated to analyze the network structure and identify key elements.

6.3.1. Indicators analysis

The DSM also enables us to compare each stakeholder using network-based indicators, thereby gaining a better understanding of their influence on the network and, consequently, on the decision-making process. This comparison is presented in Table 8, which includes several relevant network theory indicators introduced in Section 5.3.1.

An initial analysis of stakeholder connectivity reveals that many stakeholders have non-null relationships with others, indicating a highly connected network. Betweenness, closeness, and harmonic centralities are indicators of a stakeholder's connection to the rest of the network. They have pretty high values, notably for the region. The analysis reveals that high-level public stakeholders, namely the region, the Ministry of Transportation, the national government, and the European Union, are firmly connected, which is consistent with their institutional roles in transport governance.

Quantitatively, the region (A1) stands out as the most influential stakeholder in terms of interaction weight, with the highest normalized weight (0.1). It is also identified as the most structurally central node in the network, with the top normalized degree centrality (1.94) and betweenness (0.101). Although other stakeholders, such as the Ministry (A2) and Government (A3), present relatively high weighted links (0.075 and 0.066, respectively), their network centrality is significantly lower, confirming the region's unique position as both a hub of input and a structural coordinator. This means that while their influence is substantial, their network embeddedness is more limited.

The Rolling Stock Manufacturer (A5) is the second most connected stakeholder by degree centrality (1.71), with a high normalized weight (42), suggesting it is highly involved operationally. Other industrial stakeholders, such as electricity providers (A6) and railway network operators (A12), also have high weights (0.064 and 0.061, respectively). Yet, their structural role in the network is less central (degree centrality of 1.41), suggesting they are essential contributors to only a limited number of stakeholders. By contrast, local stakeholders and consultancy stakeholders show both low weight and weak structural integration, confirming their status as secondary influencers.

6.3.2. Weight analysis

An analysis of the weight of each stakeholder in the decision-making process, including weighted out-degree, in-degree, and their sum (called the total node weight), shows that 10 of 18 stakeholders have strong values, exceeding 30. That represents, on average, 10 links of value 3, which is a significant amount. Once the edge weight has been set, we can sum each node's weight along rows and columns to obtain a global weight, and divide it by the total weight of all stakeholders to obtain P_i, the relative influence of a stakeholder on the decision. The stakeholders' proportional weight in the decision-making, detailed in Table 8, is represented in simplified form in Fig. 3. A stakeholder group's weight is defined in the circle, with a focus on the region's weight.

Fig. 3 shows that the most influential stakeholder in the decision-making process is the region. AOTs decide which technologies to

Table 8
Stakeholders' network indicators regarding train decarbonization.

Stakeholder's ID	Actor's Name	Number of Outputs Ω+	Number of Inputs Ω-	Weighted Out-Degree φ+	Weighted In-Degree φ-	Normalized weight φ	Normalized Degree Centrality Ω	Normalized Betweenness Centrality Cbet	Normalized Closeness Centrality Cc	Harmonic Centrality Ch
A1	Region	16	17	45	56	0.100	1.94	0.101	0.944	16.5
A2	Ministry in charge of transportation	14	14	36	40	0.075	1.65	0.028	0.850	15.5
A5	Rolling stock manufacturer	13	16	33	42	0.074	1.71	0.023	0.810	15
A11	SNCF Réseau	14	14	29	38	0.066	1.65	0.018	0.850	15.5
A3	French government	13	14	36	31	0.066	1.59	0.023	0.810	15
A6	Electricity producers and distributors	12	12	34	31	0.064	1.41	0.031	0.773	14.5
A4	European union	13	14	35	29	0.063	1.59	0.023	0.810	15
A12	railway network operator	12	12	28	34	0.061	1.41	0.032	0.773	14.5
A9	Industry stakeholders	11	14	32	26	0.057	1.47	0.016	0.739	14
A7	Hydrogen producers	12	11	33	24	0.056	1.35	0.011	0.773	14.5
A8	Infrastructures constructors	12	10	33	23	0.055	1.29	0.014	0.773	14.5
A10	Diesel producers	11	11	30	24	0.053	1.29	0.011	0.739	14
A13	DGITM	9	12	25	26	0.050	1.24	0.009	0.680	13
A14	Engineering consultancy	9	10	22	20	0.041	1.12	0.006	0.680	13
A16	EPSF	7	8	15	23	0.037	0.88	0.014	0.630	12
A18	Local authorities in the regions (departments. EPCI. cities...)	11	11	6	29	0.035	1.29	0.012	0.739	14
A17	Other territory stakeholders Associations (users, environmental...)	5	3	15	9	0.024	0.47	0.001	0.586	11
A15	Régions de France	10	1	20	2	0.022	0.65	0	0.708	13.5

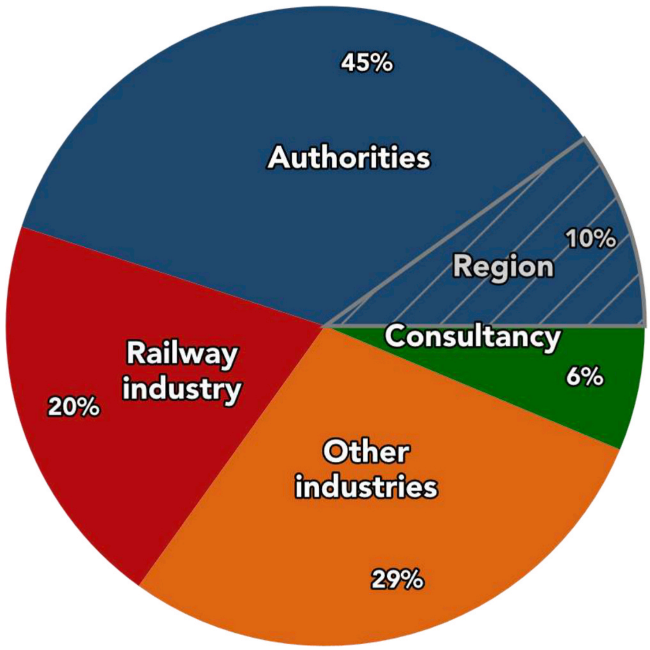

Fig. 3. Stakeholders' weight on the decision-making pie chart.

implement in their territory, accounting for nearly 10% of the weight. The lowest influence on the decision-making process comes from "Régions de France" with 2.2%. This distribution of decisional power among other stakeholders is relatively balanced. The different stakeholders, which collectively weigh over 6%, include electricity producers and distributors, Railway network operators, SNCF Réseau, rolling stock manufacturers, the European Union, the French government, and the Ministry in charge of transportation. We notice that they are all Railway industries or public authorities, except for electricity producers and distributors.

We also grouped some stakeholders by similarity to analyze their influence as a family. Private stakeholders in the railway sector were grouped under "Railway industry." "Other industries" group the more specialized industry stakeholders. These two groups, combined, represent the private sector's influence on the decision-making process at 49%. The consultancy stakeholders for regions are regrouped under "consultancy," while the public authorities are grouped under the "Authorities" label. They have a combined influence of 51% on the decision-making process. Together, their cumulative weight significantly prevails over the regions' weight in the decision-making process, highlighting the AOT's strong dependence on external stakeholders for strategic decisions.

6.3.3. Connectivity analysis

The normalized betweenness centrality provides complementary insights into the structural role of stakeholders as intermediaries within the decision-making network, as it captures the extent to which a stakeholder lies on the shortest paths between other stakeholders and thus controls the circulation of information, resources, or influence. The results show that the region again occupies the most central intermediary position, with the highest normalized betweenness value (0.101), confirming its pivotal role between otherwise partially disconnected stakeholders. Electricity producers and distributors (0.031), the railway network operator (0.032), and the Ministry in charge of transportation (0.028) also display relatively high betweenness values, indicating that they act as critical transmission nodes between public authorities and industrial stakeholders. In contrast, several stakeholders with significant weighted influence, such as hydrogen producers, infrastructure constructors, and diesel producers, exhibit much lower betweenness values (around 0.01), indicating that their influence is primarily through direct interactions. At the lower end of the spectrum, "Régions de France" and territory stakeholders associations show near-zero betweenness, indicating a marginal role in inter-group coordination despite their presence in the network.

These results highlight a structural asymmetry: some stakeholders dominate through the volume of interactions, while others dominate through their ability to connect otherwise separate parts of the decision-making system. This result reveals that the regions play a central connective role in structuring interactions across the entire decision-making network, as illustrated in Fig. 4.

6.4. Step 4: Interaction-based clustering of stakeholder network

Following the structure of step 4 presented in Section 5.4, this section applies clustering algorithms to the DSM, refines the resulting clusters using decision-makers' insights and stakeholder network indicator analysis, and then assesses the sensitivity of the clusters.

6.4.1. Initial clustering from algorithms

We applied the algorithms introduced in Section 5.4.1: Leiden and Girvan-Newman methods. The clusters are represented in Fig. 5, and the raw matrix format is shown in Table 9. The clustering analysis revealed three key insights.

First, both algorithms propose the same two clusters. The region is the common element between these two, as they both use non-disjoint clustering, which allows a stakeholder to belong to multiple clusters. The first cluster (C1) comprises industrials with an informative workflow that leads to the informative private-to-public cluster. This informative private-to-public cluster comprises public stakeholders, such as regional Authorities and DGITM, the railway industry, consultants, and energy-oriented industrial sectors, including diesel producers, hydrogen producers, and other industry stakeholders. A second local-strategies cluster (C2) comprises local industrial and public entities.

6.4.2. Objective-driven reorganization of stakeholder clusters

Second, a post-treatment analysis of cluster C1 shows a sub-cluster of higher density, including the region, the Ministry, the DGITM (strongly connected to the region), two entities related to the infrastructure and operation of the network (SNCF Réseau and the Railway network

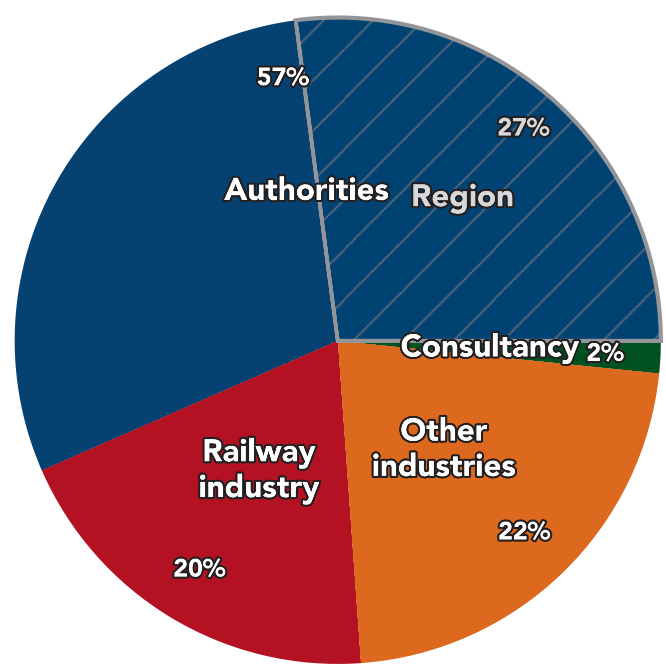

Fig. 4. Stakeholders' centrality on the decision-making pie chart.

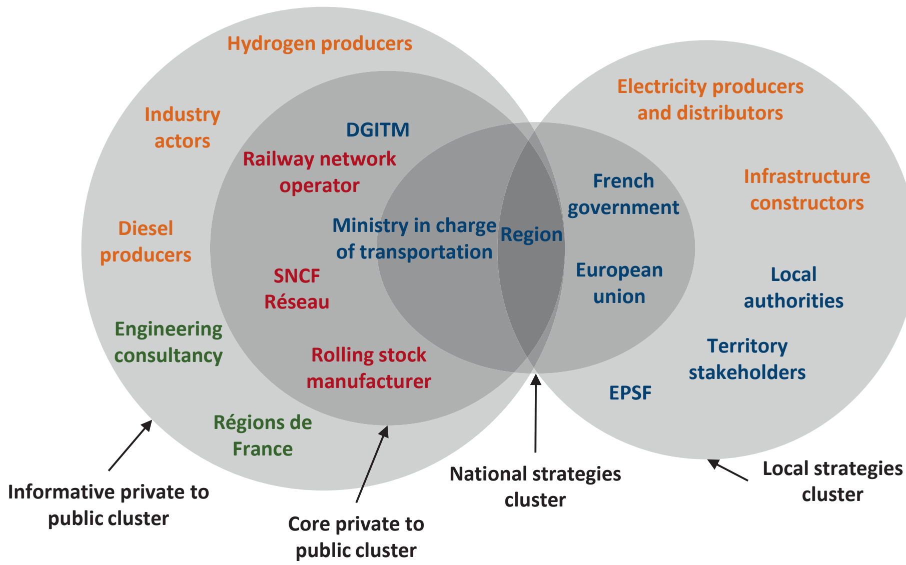

Fig. 5. Clusters representation.

Table 9
The clustered DSM.

	A7	A9	A10	A14	A15	A11	A12	A5	A13	A2	A1	A3	A4	A18	A6	A16	A17	A8
A7				3	2	1	1	3	3	3	3	3	3	-1				
A9	1		1	2	2	1		3	3	3	3	3	3	-1	1			1
A10				3	2	1	1	3	3	3	3	3	3	-1				
A14	2	2	2		2	2	2	2		2	2							2
A15											2							
A11	3	3	3	2	2		2	3		3	3	3	3	2	3			3
A12	3	3	3	2	2	3		3	3		3				3	3		3
A5	3	3	3	2	2	3	3		3	3	3	3	3	-1	3	3		3
A13	3	3	3	**C1**		4	4	1		1	-1	1	1		3			3
A2	3	3	3			4	5	1			4	3	3	1	3	1	3	3
A1	3	3	3	2	2	4	4	6	3	4		4	3	3	3	3	3	3
A3	3	3	3			1	1	1		1	4		3	1	3	1	3	3
A4	3	3	3			1	1	1		1	4	1		1	3	1	3	3
A18	3	3	3						1	3	3	3	1		3		3	3
A6	3			3	2	1	1	3	3	3	3	3	3	3		**C2**		
A16		3				2		3		3	3	3	3					3
A17							3								3	3		
A8				3	2	1			3	3	3	3	3	-1	3			

operator), and, more surprisingly, a private stakeholder, the Rolling Stock manufacturer. However, as seen in the previous indicator analysis, this private stakeholder plays a specific role in the network. Its inclusion into a higher-density sub-cluster of C1 confirms its particular influence. That means the communication frequency should be higher, with greater consideration of its constraints.

Third, a dense kernel of public institutions at various levels, including the region, the Ministry, the government, and the European Union, has been identified post-treatment and is referred to as the “national strategies” cluster. It is expected to have strong relationships, even if it does not mean that a specific way of organizing and communicating is relevant in that case. There are already formal, recurrent communication circuits between these stakeholders. To minimize the influence of private stakeholders on the decision-making process, we configured this cluster to isolate the most significant public stakeholders to train decarbonization into a central cluster. That setup facilitates a structured interaction where the core public cluster can maintain initial deliberations insulated from private interests.

6.4.3. Sensitivity analysis of atypical interaction values

As a methodological check, we also analyzed the influence of negative values on the algorithm's results (Table 10). There are only a few “-1″ values, so removing these values does not affect clustering. However, from a practical point of view, we have analyzed what the presence of a ”-1″ represents in a cluster and, therefore, in a communication circuit between cluster stakeholders. From a practical point of view, we can keep both stakeholders in the cluster or remove one of them. A “-1″ exists in the sub-cluster of C1 between A13 and A1, who is our decision-maker. Moving one of the two stakeholders involved in the ”-1″ relationship is possible. That would correspond here to moving A13 out (of the sub-cluster), as A1 is the network's central node. The second “-1″ is between A18 and A8 in the bottom right-hand cluster C2. It takes work to

Table 10
Clustered DSM considering −1 values.

	A7	A9	A10	A14	A15	A13	A11	A12	A5	A2	A1	A3	A4	A18	A6	A8	A16	A17
A7				3	2	3	1	1	3	3	3	3	3	-1				
A9	1		1	2	2	3	1		3	3	3	3	3	-1	1	1		
A10				3	2	3	1	1	3	3	3	3	3	-1				
A14	2	2	2		2		2	2	2	2	2					2		
A15											2							
A13	3	3	3				4	4	1	1	-1	1	1		3	3		
A11	3	3	3	2	2			2	3	3	3	3	3	2	3	3		
A12	3	3	3	2	2	3	3		3		3				3	3	3	
A5	3	3	3	2	2	3	3	3		3	3	3	3	-1	3	3	3	
A2	3	3	3				4	5	1		4	3	3	1	3	3	1	3
A1	3	3	3	2	2	3	4	4	6	4		4	3	3	3	3	3	3
A3	3	3	3				1	1	1	1	4		3	1	3	3	1	3
A4	3	3	3				1	1	1	1	4	1		1	3	3	1	3
A18	3	3	3			1				3	3	3	1		3	3		3
A6	3			3	2	3	1	1	3	3	3	3	3	3				
A8				3	2	3	1			3	3	3	3	-1	3			
A16		3					2		3	3	3	3	3			3		
A17								3							3		3	

choose which stakeholder to move, as they interact almost equally with the other stakeholders in the cluster.

Removing one of the two seems problematic, as there is no other larger cluster as in the previous case. One possible solution is to do the opposite, i.e., move one of the players to the center of the network rather than to the periphery. In this case, stakeholder A18 could be proposed in the central cluster, the core. Indeed, it is a public player, like the other components of this core. However, from a purely mathematical perspective, stakeholder A8, a private stakeholder, interacts most with the core stakeholders. We thus find ourselves in an interesting case of divergence between mathematical and practical logic. We cannot formulate a proposal at this stage, as these refinements would have to be proposed to decision-makers, who might also adopt a different strategy depending on the region and its local context. That is a conceptual proposal for treating the "-1" values in the matrix.

6.5. Step 5: Temporal allocation of stakeholder contribution

Our objective is to limit stakeholder contributions to the decision stages where their involvement is required. Table 4 details the stakeholders needed for each decision stage. Using the clusters built in Section 6.4 (see Fig. 5), we identify the stakeholders with whom they interact most closely. By keeping clusters together, we preserve network integrity. By restricting stakeholder contributions to the decision stages where they are required, we mitigate the risks associated with ill-timed or inappropriate intervention, as identified in Section 2.2. Therefore, a reorganization of stakeholders' contributions alters power dynamics and enhances the robustness of outcomes (see Table 11), thereby addressing gaps (see Table 4) between the stakeholders expected and those involved at different stages of the decision-making process.

Limiting *data evaluation* to the railway industry and the public authorities with which it is most closely connected allows for an exchange equilibrium limited to essential industrial stakeholders. For the *development of criteria*, the discussion must be opened to more stakeholders as the impact concerns and depend on a larger number of public and private stakeholders. Once these criteria are set, the *performances simulation* can be restricted again to the core private-to-public cluster, as the railway data are provided by its stakeholders to allow for a *preliminary technological comparison*. The *multiple criteria analysis*, which considers both environmental and economic factors, should collect as much data

Table 11
Proposition at the cluster level of stakeholders' intervention in the decision stages.

Stage	Identified Clusters	Expected impact (compared to the existing situation, Table 4)
1. Data evaluation	Core private to public cluster	Provides an equilibrium of public and private stakeholders. Adds national stakeholders, allowing better insight into national strategies. Limit private stakeholders to railway stakeholders; only the necessary stakeholders at this stage.
2. Development of Criteria	National strategies cluster Informative private-to-public cluster	Discussion needs to be done with national public stakeholders to align with their strategy. Opening the discussion to a larger panel of private stakeholders allows for the identification of all decision criteria and involves industrials in their development. Involving consulting entities to mitigate private stakeholders' influence.
3. Performances simulation	Core private to public cluster	The simulation is a sensible part of the decision process, and its parameters need to be protected from private parties; hence, the use of the private-to-public cluster. Railway stakeholders are essential to its development.
4. Preliminary Technological Comparison	Core Private to public cluster	The results of those first stages of the analysis provide the basis for the multiple criteria analysis. The use of this cluster is justified for the same reasons.
5–6. Multiple Criteria Analysis	Local strategies cluster Informative private to public cluster	An extensive set of stakeholders is needed to obtain the data required for this stage. All the stakeholders are involved. We use the two larger clusters to limit the exchanges to the relevant stakeholders.
7. Technical and Political Validation	National strategies cluster	Returning to exchanges with the national strategies cluster allows for validation and communication of the decision reached.

as possible from stakeholders. Therefore, it should be open to two different clusters in parallel: local strategies and informative private-to-public clusters. *Technical and political validation* does not need private parties and should be limited to the national strategies cluster. The representation of decision stages (Fig. 1) was populated thanks to the clusters (Fig. 5) resulting in Fig. 6.

The step-by-step identification of stakeholders to involve enables a more thorough decision-making process, while limiting private-sector influence and encouraging exchanges among public stakeholders. These analyses, both individual and stakeholder group analyses, as well as the proposal of clusters and their positioning throughout the decision-making process, would not have been possible without the use of specific network-theory-based approaches.

7. Discussion

This Section discusses the current state of validation for the different parts of our proposal, starting with the matrix-based stakeholder network modeling and the application of network theory to analyze this network. Thus, a region's feedback is provided on the final output of this work, which involves the reshuffled organization of the decision-making process, considering the temporal allocation of stakeholders. Finally, some contributions to the general field of transportation research are outlined in paragraph 7.4.

7.1. Steps 1 & 2: Validation of the matrix-based DSM approach

Three successive representations were tested to illustrate stakeholders' relationships and interactions:

(i) The initial orbital graph is represented in Fig. 2
(ii) A spaghetti graph
(iii) A DSM presented in Table 7

The initial representation, centered around the final decision-maker, captures most of the relationships and offers a clear view of the network. However, the analysis of interviews reveals missing connections or poorly detailed workflows. The spaghetti graph addresses the lack of completeness by representing all relationships; however, it increases graphical complexity and decreases readability. Finally, thanks to the DSM, all relationships and workflows among stakeholders are captured, and the complexity is illustrated in a way that facilitates further analysis. The DSM approach finally overcomes both the incompleteness characterizing the initial network and the spaghetti graph's lack of understandability, as depicted in Fig. 7. This experimentation validates that the DSM is the most suitable approach for representing and analyzing the complex stakeholder network in this specific context.

7.2. Steps 3 & 4: Synthesis and validation of the application of network theory in our context

The DSM analysis yielded insightful findings regarding the weight and interconnectedness of stakeholders. Overall, these results reveal a network in which the weight is relatively evenly distributed among stakeholders, with decision-makers neither overly dominant nor poorly connected. This structure reinforces the relevance of cluster analysis to better understand coalition dynamics and hidden groupings within this socio-technical governance system:

- Regions (AOTs) dominate the weight of individual stakeholders, but the private sector accounts for a substantially larger share of the decision-making weight. 49% of the total weight in the decision process comes from private stakeholders with a vested financial interest in the outcomes.
- Regions also exhibit strong centrality in the network, suggesting potential leverage points to moderate private sector dominance through network management.
- Higher-level authorities and railway industrials occupy the upper end of the weight distribution. This can be explained as the first influence on the roadmaps and funding, and the second impact on research orientation.

Interviews with decision-makers validate these results. Industrial stakeholders are identified as exerting excessive power on the decision-making process:

"*Alstom chose batteries with high energy density, meaning long range but with low charging capacity […] this choice does not allow the trains to operate continuously throughout the day.*" "*These difficulties could have been avoided if the region had had oversight over the functional specifications defined in the SNCF–Alstom contract.*" "Nouvelle-Aquitaine"
"*The choice to place trust in Alstom was pushed by a regional Councilor who was a Member of Parliament at the time.*" "Régions de France"
"*What we can do depends a lot on the offer from the manufacturers.*" "Corse"
"*For now, the only simulations we have come from Alstom.*" "Provence-Alpes-Côte d'Azur"
"*Today, for many regions, rolling stock basically means Alstom.*" "Bretagne"

The risk identified regarding industrial alliances is also supported by empirical evidence:

"*The region has no oversight over the contract signed between SNCF and Alstom for the installation of battery trains.*" "Nouvelle-Aquitaine"
"*ALSTOM, together with SNCF, is leading the project to adapt a Régiolis H_2 trainset.*" "Nouvelle-Aquitaine"

Low-influence entities, as indicated by indicators (see the last stakeholders in Table 8 ranking), are primarily local stakeholders, including local authorities and other territorial stakeholders.

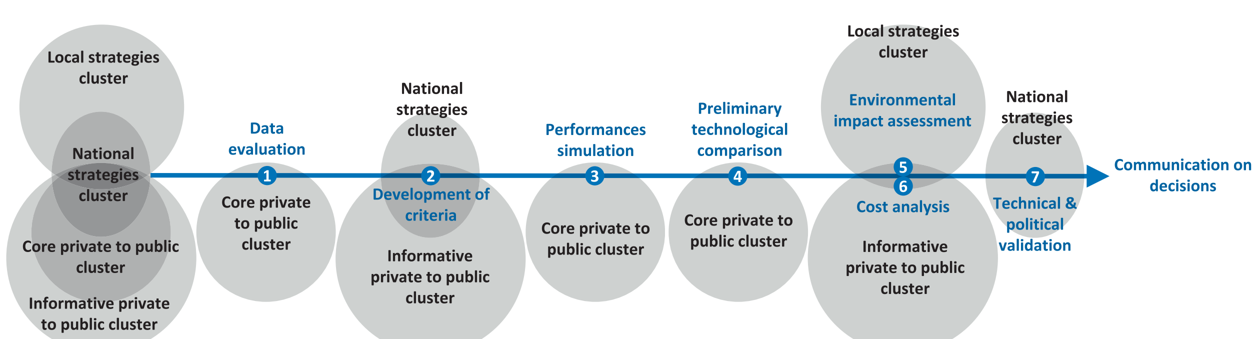

Fig. 6. Clusters intervention in the decision stages representation.

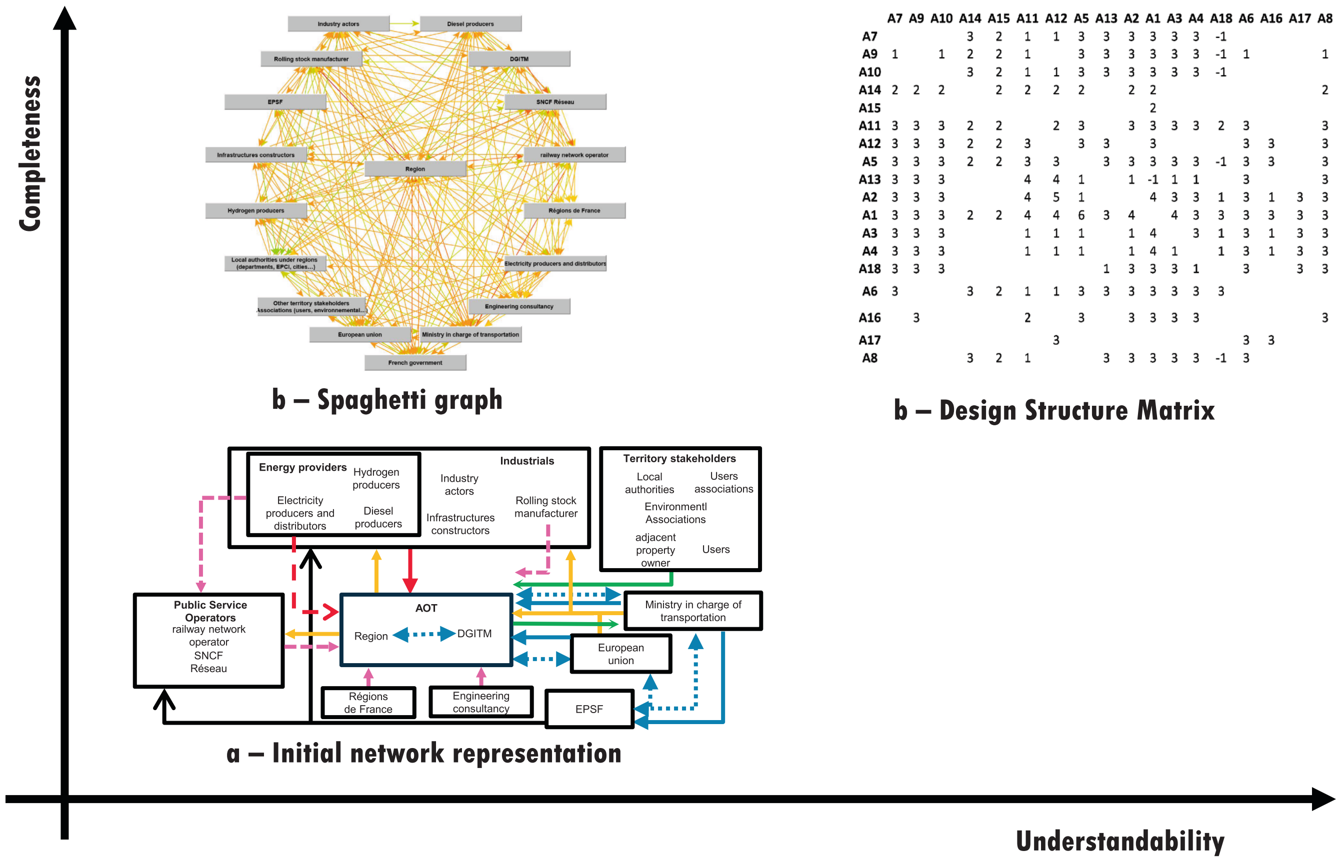

Fig. 7. Stakeholders network representation completeness and understandability.

Clustering the network offers a new perspective on the stakeholder network. The centrality of the national strategies cluster allows for synergies with higher public authorities. A highlight on “SNCF Réseau“ and “Rolling stock manufacturer” from the core private to public cluster deserves special attention for their potential influence. These two industrial stakeholders, among the top seven in centrality indicators, underscore the importance of industry in the decarbonization narrative. Their position indicates a level of influence significant enough to affect the network dynamics. While other Industry Stakeholders in the decision-making process demand vigilance, limiting their intervention to designated decision stages helps mitigate their impact. The parallel intervention of independent consultancy organisms equilibrates the strengths at work.

To conclude on the usefulness of the network theory approach for detecting and proposing relevant, non-trivial elements, we begin by asserting that the current close circle of decision-making comprises decision-makers and certain private entities. This situation is further exacerbated by the reliance on information about technologies that are predominantly lacking among industrial stakeholders. Currently, there is a lack of mechanisms for independent third parties or public organizations to systematically gather and verify such critical data. The predominance of private parties with financial interests in decision-making circles introduces a bias that could skew decisions in favor of specific technologies or solutions, regardless of their overall alignment with decision-makers' criteria. This situation raises concerns regarding the integrity and transparency of the decision-making process. To mitigate the risks associated with lobbying and ensure a more objective and transparent decision-making process, implementing actions to organize stakeholders' communication, coordination, and decision-making will aid strategic planning and informed decision-making for the decarbonization of regional trains.

7.3. Step 5: Decision-making process reorganization validation: The “Corse” interview

The cluster-based reorganization of the decision-making process was presented to a decision-maker during a final interview conducted in “Corse”. This exchange allowed us to assess the operational credibility of the approach from the perspective of a regional authority involved in train decarbonization decisions. The interviewee confirmed the necessity of a sequential and role-differentiated organization of the process, stressing that “at each stage, there is a specific level of discussion” and that “the region defines the need, the operator checks whether it works, and the manufacturer proposes a solution.” This feedback validates the principle of targeted stakeholder involvement underlying the clustering approach. The necessity of restricting industrial interactions to clearly identified phases was also explicitly confirmed: “during the tendering phase, we are not supposed to discuss with them for reasons of fairness.” Rather than emphasizing the control of industrial influence as such, the validation primarily concerns the need for a structured sequencing of interventions, a clear separation of roles, and a centralized coordination to avoid dispersion of responsibilities. Additionally, the interview highlighted the importance of stabilizing the decision process, as the interviewee emphasized that “the key is to take the time upstream to clearly define the needs and ensure everything is stabilized before starting discussions with manufacturers.” Overall, this validation confirms the practical relevance of the proposed reorganization of the decision-making process and its consistency with the regional operational constraints and governance requirements.

7.4. Positioning our contribution in the field of transportation research

Recent contributions have emphasized the need for interdisciplinary, methodologically plural, and practice-oriented approaches to address complex transportation decision-making problems. Prior studies have developed decision frameworks under similar risks in rail transportation contexts (Koohathongsumrit et al., 2024; Norouzi et al., 2025). In parallel, there is a venue for innovative decision-analytic approaches dealing explicitly with policy robustness in the analysis of transport climate policies (Engholm & Kristoffersson, 2025). The literature has also highlighted the importance of socio-political governance dimensions in transportation systems, including policy implementation challenges and stakeholder dynamics, as illustrated by Knamiller et al. (Knamiller et al., 2024). More recently, methodological contributions have explored decision support frameworks that integrate emerging tools, such as synthetic stakeholders and stakeholder network analysis, to capture multi-actor interactions and decision processes better (Manzolli et al., 2025). The present study builds directly on this body of work by proposing a structured decision support methodology that combines stakeholder influence modeling and governance-aware process design, applied to the decarbonization of regional rail systems. In doing so, it aligns to foster interdisciplinary research that bridges analytical rigor with real-world policy and practice, while addressing emerging, uncertain, and socially embedded transportation challenges.

8. Conclusion

This research demonstrates that stakeholder network modeling and analysis can structure a public–private decision-making process as sensitive as choosing an alternative technology to diesel for regional trains. It thus makes three significant contributions:

(i) An original conceptual methodology that systematically integrates public and industrial stakeholders and their interactions.
(ii) A set of network-based indicators revealing the centrality and polarization of stakeholders, a basis for more transparent governance.
(iii) A reorganization of the decision-making workflow into successive clusters that limits the risk of capture by private interests, while retaining the indispensable industrial expertise.

The proposed methodology aims to bridge a gap in the literature on dynamic stakeholder organization in decision-making processes to mitigate the risks identified. It relies on tools for multi-actor network modeling, analysis, and clustering to propose a dynamic intervention structure. This methodology can be applied to any complex public–private decision-making process. In general, our proposal can be applied to all multi-stakeholder decision-making processes, not in the sense of several stakeholders contributing simultaneously to a decision, but in the sense of several stakeholders contributing at different stages of the process, usually with a central final decision-maker. The context of decarbonization in the French rail sector at the regional level (where the final decision-makers are located) introduces a specific feature: the involvement of private contributors in a decision ultimately taken by a public stakeholder. However, even on this point, we believe our proposal can be generalized to all types of stakeholders without necessarily involving this public–private mix. As such, the railway case study is a demonstrative application that illustrates the approach's transferability to structurally similar decision problems in other sectors, such as energy systems, large-scale infrastructure planning, or industrial transition projects.

In addition to these methodological contributions, the results shed light on the actual distribution of influential power of train decarbonization: the private sector holds half of the decision-making weight, which justifies the introduction of formal safeguards in the decision support system. We contribute to the research question by formalizing a decision-support methodology that positions the intervention of various stakeholders throughout the decision-making process through modeling, analysis, and clustering of the stakeholders' network.

Several perspectives for future work naturally emerge from this research.

Firstly, implementing the proposed methodology region by region to assess how territorial specificities shape stakeholder influence and decision-making structures. For instance, the "Grand-Est" region, characterized by a higher level of hydrogen production than other regions, can be expected to exhibit a higher weight of hydrogen-related stakeholders within the decision-making network (Lenz, 2024).

Secondly, transposing the method to other public–private decision contexts would provide additional experiments of the proposed methodology.

Thirdly, longitudinal studies measuring the actual impact of the proposed re-orchestration on the quality, speed, and acceptability of decisions would complete the academic and operational validation of the approach.

Finally, the development of a configurable multi-criteria module incorporating technological, economic, environmental, and social performance indicators would enable quantitative recommendations grounded in technology. This would require formalizing the data, methodology, and tools needed to eliminate and rank the technological alternatives.

CRediT authorship contribution statement

Benoît Volant: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Franck Marle:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Project administration, Funding acquisition, Conceptualization. **Yann Leroy:** Writing – review & editing, Validation, Supervision, Project administration. **Jeanne-Marie Dalbavie:** Project administration, Investigation, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Volant reports financial support was provided by IKOS Consulting. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trip.2026.101880.

Data availability

Data will be made available on request.

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