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A model for assessing maturity of hydrogen supply chain resilience: a complexity-inspired approach

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ABSTRACT

This study presents a maturity model (MM) for supply chain resilience management (SCRM) in the hydrogen sector, aimed at identifying resilience gaps and guiding improvements. The model is developed using an iterative approach combining literature review, expert interviews, and case studies. Grounded in design science research and complex adaptive systems (CAS) theory, the MM supports building adaptable, scalable supply chains that can manage regulatory shifts and industry transitions. Case study findings reveal that the development of SCRM maturity in the upstream hydrogen sector is constrained by downstream uncertainties and fragmented market mechanisms. Vertical integration across the supply chain significantly enhances hydrogen supply chain resilience. The MM offers a structured approach for hydrogen companies to improve response capabilities and apply scalable, strategy-aligned resilience measures. Theoretically, it advances understanding of CAS dynamics in SCRM. Practically, it provides managers with actionable guidance for implementing resilience strategies across the industry.

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Supply chain resilience; maturity models; performance evaluations; complex adaptive systems; hydrogen industry; design science

1. Introduction

1.1. Motivation

The COVID-19 pandemic exposed major weaknesses in conventional supply chain resilience (SCR) strategies, particularly those based on reactive measures such as contingency planning. This disruption led to a broad reassessment of supply chain design and risk management approaches (Koh et al. 2024). In an increasingly volatile environment, short-term responses are no longer sufficient. There is growing interest in developing adaptive, long-term resilience mechanisms to support operational continuity and strategic sustainability (Echefaj et al. 2024). Organisations aim to improve profitability through more robust and integrated supply chains, while also enhancing customer satisfaction and responsiveness (Sena et al. 2022). Resilience-focused planning includes anticipating customer needs and managing disruptions, with attention to delivery reliability, cost efficiency, safety, reserve capacity and recovery speed (Ivanov 2024).

SCR has gained further relevance in the global transition to a net-zero economy, where hydrogen is emerging as a key energy carrier. Despite its potential, the hydrogen

sector faces challenges in scaling and long-term viability, particularly under industrial and infrastructure uncertainty (Sgarbossa et al. 2023). Resilience in hydrogen supply chains (HSCs) is an operational issue with public relevance, given their links to policy, infrastructure and stakeholder expectations (Rajabzadeh and Wiens 2024). Building resilient HSCs requires more than restoring performance after disruptions. It demands adaptive capabilities that respond to changing demand, technologies and regulations, operating within complex, interconnected business systems (Ivanov 2024). As resilience needs become more specific in the hydrogen sector, structured tools are increasingly required to assess and guide its resilience capacity over time.

Performance evaluation frameworks in supply chain management are broadly divided into performance measurement and maturity measurement (Bueno et al. 2025). Performance measurement tools provide general indicators, whereas maturity approaches offer phase-based frameworks to track how specific capabilities develop over time. Maturity models (MMs) conceptualise progression towards a desired state by defining key process traits at each stage and the transitions between

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them (de Andrade, Gusmão, and Silva 2021). They have been successfully applied in areas such as artificial intelligence (Fornasiero et al. 2024) and operations planning (Ferraro et al. 2023). Empirical evidence shows that maturity-based approaches improve operational outcomes by revealing opportunities for optimisation and progressive development (Bititci et al. 2014).

Despite growing interest in SCR, models that explicitly address SCR management (SCRM) maturity are still recent and underdeveloped (Roque Júnior, Frederico, and Costa 2023). No standardised framework currently assesses how resilience capabilities evolve in high-stakes, emerging sectors such as hydrogen. Hydrogen SCRM maturity calls for value chain-wide assessment of production systems and the broader ecosystem (Sgarbossa et al. 2023). Addressing this gap, this study develops a conceptual MM for HSCs, providing a structured, long-term approach to building and evaluating resilience in this strategically vital sector.

1.2. Research aim

Given the early stage of hydrogen energy, related production systems and applications, this study develops a Complex Adaptive Systems (CAS)-based MM specifically for HSCs. The model supports the evaluation of SCRM capabilities across different phases of industrial development. The study is guided by two research questions:

1. How can a complexity-inspired maturity model represent and manage the evolution of HSCs, while incorporating resilience capability assessment?
2. How effective is the proposed maturity model in identifying constraints to HSC resilience?

The model was developed by analysing companies within HSCs, focusing on internal and external factors that shape SCRM. Grounded in CAS theory (Kong et al. 2025), the MM evaluates HSC resilience through operational, organisational and technical capabilities relevant to hydrogen supply. The CAS lens highlights interdependencies between social and ecological systems and interactions among key actors, while incorporating spatial resilience by considering structural and spatial patterns. Situating HSC resilience within the wider business ecosystem captures complex links across upstream and downstream value chains, ensuring that assessments reflect evolving sector dynamics and support more sustainable transitions.

The paper is structured as follows: Section 2 reviews the literature on HSC resilience and MMs in supply chain management. Section 3 outlines the methodology and model development process. Section 4 presents and

analyses the proposed model, followed by a discussion of its applications in Section 5. Section 6 concludes and outlines future research directions.

2. Conceptual and theoretical basics

SCR refers to the adaptive capacity to anticipate, respond to, and recover from disruptions while maintaining operations and progressing toward a more resilient state (Han, Chong, and Li 2020). Melnyk et al. (2014) identified SCR as a supply chain management concept for mitigating vulnerabilities, yet its conceptualisation remains debated. Kong et al. (2025) clarify HSC resilience by defining it through a CAS perspective. Table 1 summarises existing SCRM dimensions based on Han, Chong, and Li (2020) and Singh, Soni, and Badhotiya (2019), while Section 4 adapts these indicators to hydrogen-specific contexts. For example, previous research distinguishes ‘visibility’ (real-time monitoring and traceability) from ‘IT capability/information sharing’ (data exchange via technology) (Kamalahmadi and Parast 2016). Here, visibility includes both technical systems and organisational collaboration, combined into the operational criterion ‘Visibility and Transparency’. Commonly cited capabilities such as redundancy, agility, and flexibility are incorporated, alongside sustainability and adaptability within operational resilience (Shishodia et al. 2023).

Theoretical explorations of SCR often rely on frameworks such as Dynamic resource-based view, Dynamic Capability Theory, Resource Orchestration Perspective, and Contingency Theory, which provide firm-centric views but lack a systemic outlook (Gong et al. 2018; Huang et al. 2023). While Systems Theory considers SCR a systemic property, it inadequately addresses evolution in dynamic supply chains (Raj et al. 2015). Given the uncertainty and emerging characteristics of hydrogen industry, a more dynamic framework is needed (Kong et al. 2025). CAS theory conceptualises adaptive interactions and emergent behaviours across multiple system levels (Ghazzawi, Kuziemy, and O’Sullivan 2016). This perspective is particularly relevant for energy-sector supply chains critical to sustainable development but likely impacted by external conditions. CAS Theory thus provides a robust foundation for addressing theoretical gaps and advancing SCR in the HSC context.

Recent studies examine SCR in oil and gas (Seferlis et al. 2021). Liu et al. (2020) propose a network integrating multiple sources and hydrogen energy recovery, while Bag et al. (2025) extend organisational information processing theory to the GH₂ industry, linking effective information processing to resilience under high uncertainty. However, few works adopt a system-based view or treat resilience as a multi-scale, evolving property (Roque

Júnior, Frederico, and Costa 2023). Building on Kong et al.'s (2025) multi-layered CAS-based framework, this paper develops a tailored MM to assess HSC development. The following sections detail the model's design process.

3. Methodology

Design Science Research (DSR) generates scientifically valid and practical knowledge by offering prescriptive guidance, from concrete artefacts to design principles and full design theories (Gregor and Zwikael 2024). This study applies DSR to develop a novel MM. Although DSR has limitations (Barata, da Cunha, and de Figueiredo 2023), subjective design choices were reduced by following Hevner et al.'s (2004) structured methodology and obtaining timely feedback from multiple researchers and stakeholders. The risk of dominant perspectives was further mitigated through a mixed-methods approach that combined expert interviews, fuzzy SWARA and triangulated data from the literature and company reports (Barata, da Cunha, and de Figueiredo 2023). Grounding the MM in CAS theory strengthens both its practical relevance and theoretical rigour.

The research followed an iterative process of literature review, interviews, multiple case studies and expert evaluations to refine and enhance the MM's effectiveness and usefulness (Becker, Knackstedt, and Pöppelbuß 2009) (Figure 1). The following sections detail this process.

3.1. Conception phase

Before developing the MM, a conception phase involved a systematic literature review to examine HSC resilience and SCR practices, identify key challenges, and define the model's scope, objectives and characteristics. From this, the MM's dimensions, features and indicators were distilled, leading to an initial draft of maturity levels and measures. The MM draws on multidisciplinary literature (Kong et al. 2025) and Roque Júnior, Frederico, and Costa's (2023) MM.

3.2. Design phase

The preliminary MM was developed through semi-structured interviews to verify its dimensions, capabilities, maturity levels and measurement instrument. Iterative expert reviews refined the model until saturation was reached (Becker, Knackstedt, and Pöppelbuß 2009). Purposive and snowball sampling were used to recruit experts with substantial HSC experience, based on: (1) at least five years in the hydrogen industry, (2) senior or safety management roles, and (3) direct involvement in

hydrogen safety or risk management. Participants came from diverse sectors (Table 2). Two pilot interviews with academics refined the interview guide (Malmqvist et al. 2019). Experts then assessed and ranked the MM's criteria and dimensions. Convergence in average scores across iterations indicated model saturation and stability. A final iteration tested inter-rater reliability, confirming agreement among experts and supporting the MM's completeness and robustness (Hevner et al. 2004). All interviews were recorded and transcribed verbatim. Irrelevant content (e.g. modal particles) was removed before thematic analysis, and field notes were used to capture non-verbal cues. Interviewees reviewed and validated the analysis. The MM was refined after each interview. In total, 28 interviews were conducted, balancing data saturation with time constraints (Sebele-Mpofu 2020). Kendall's *W* was used to address concerns about quantitative credibility (Hashemkhani Zolfani, Yazdani, and Zavadskas 2018), while insights from a systematic review of 103 HSC resilience studies (Kong et al. 2025) mitigate this limitation.

Data were analysed using thematic content analysis (Nowell et al. 2017) in NVivo 14. Codes were assigned to data segments, grouped into categories and then developed into themes. Dimension and criteria rankings were examined using fuzzy SWARA, addressing research question one.

3.3. Validation phase

The validation phase validates the model's accuracy and repeatability. An internal pilot study first addressed practical issues, with feedback from academics leading to refinements. This was followed by expert evaluations, during which clarity and completeness of the model were discussed and adjusted with company participants (Dunzer et al. 2025). Seven case studies answering research question two by assessing its practical application across HSCs.

4. Results

4.1. Preliminary MM

4.1.1. MM indicators and criteria

As outlined in Section 2.1, prior studies identified key SCR criteria. Building on these, this MM applies general SCR principles, defines dimensions and criteria, and organises hydrogen-specific indicators. An iterative content analysis, combining inductive and deductive reasoning, ensured alignment between HSC indicators and established SCR concepts (Singh, Soni, and Badhotiya 2019).

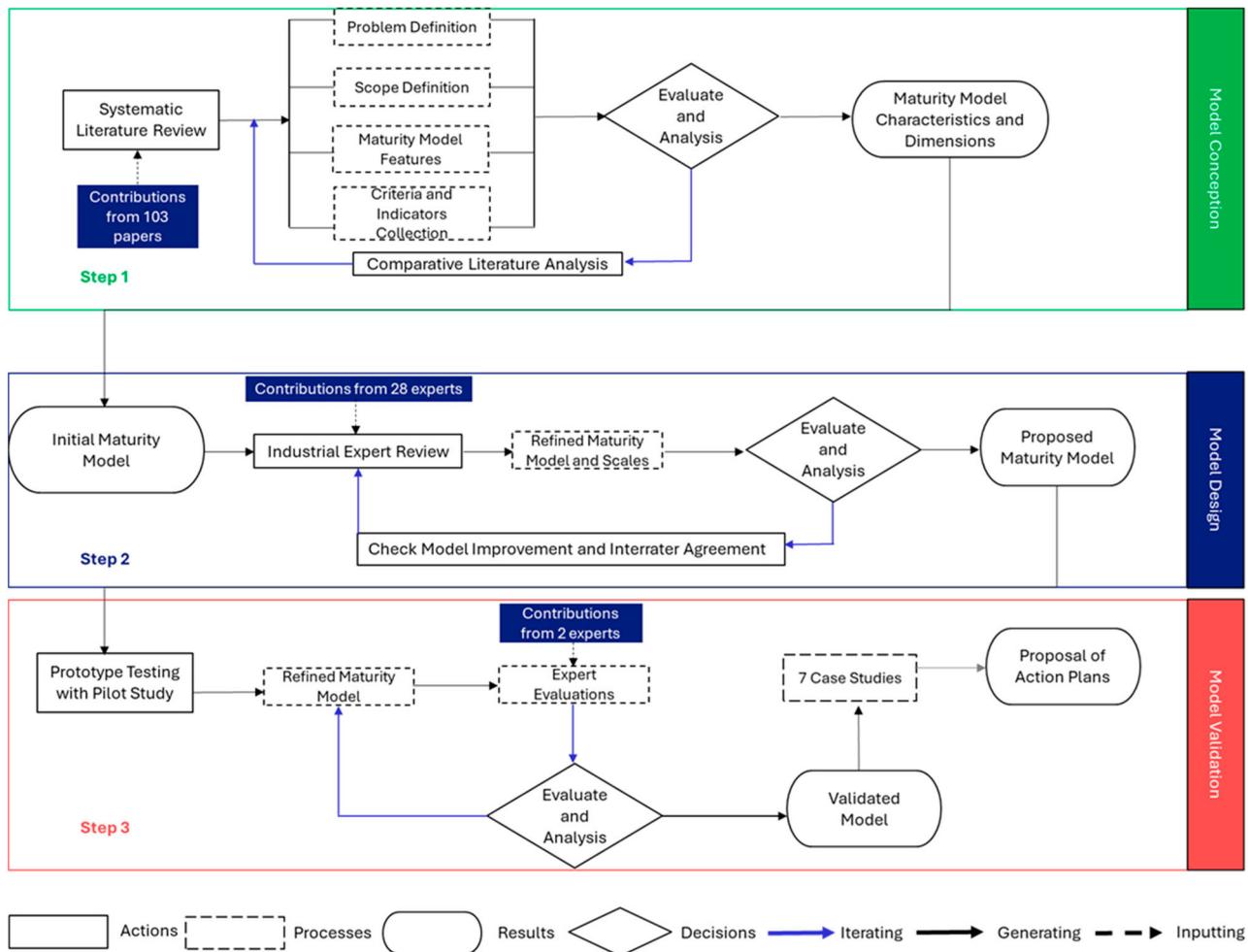


Figure 1. Research methodology, redrawn from (Becker, Knackstedt, and Pöppelbuß 2009).

First-order concepts from 103 hydrogen resilience sources and second-order SCRM themes informed third-order elements in the technical, organisational, and operational domains, offering a concise yet holistic view of HSC-specific risks (Kong et al. 2025; Siawsh et al. 2019). The first iteration focused on coding MM components, and the second integrated updated HSC literature, CAS and SCRM insights, and peer feedback. CAS theory guided the categorisation of indicators through a business ecosystem lens and the adaptation of SCRM concepts to hydrogen contexts. The MM's indicators and sub-criteria across the three dimensions are presented in Supplementary Table 1.

4.1.2. Preliminary maturity levels

The preliminary MM did not include quantitative weighting. Instead, expert evaluations were used to rank and synthesise criteria into the final model. CAS theory shaped the maturity structure, supporting progression from reactive to proactive capabilities and from manufacturing-level resilience to ecosystem integration

(Nair and Reed-Tsochas 2019). Maturity levels were validated through expert interviews. Adapting Roque Júnior, Frederico, and Costa's (2023) model, the MM advances through four stages of resilience maturity:

- Initial: minimal awareness or application of resilience (levels 1–2)
- Intermediate: initial recognition and implementation of core constructs (levels 2–3)
- Advanced: strategic integration with data-driven management and coordination (levels 3–4)
- Business ecosystem: alignment with sustainable development goals at industry level (levels 4–5).

4.2. Proposed MM

The preliminary MM was validated through expert interviews, resulting in the final version shown in Figure 2. It comprises five levels representing stepwise resilience development: the first three focus on internal capability building (manufacturing perspective), while the

Table 2. Demographics of the interviewees. s = sector, indicated by capitalised abbreviations: S (Supplier), EM (Electrolysers Manufacturer), FS (Feedstock Supplier), FC (Fuel Cell Supplier), CCS (CCS Supplier), C (Consulting), ST (Hydrogen Storage), eM/H (experience, Medium 5–10 years, High 10 years and over), cS/M/L (Company size, Small fewer than 50 employees, Medium 50–200 employees, Large over 200 employees) rUK (region, UK). So that: Interviewee (I) corresponds to: sector = Supplier, experience = High, company size = Large, region = UK.

Interviewee	Sectors	HSC functions	Positions	Years of experience	Company size	Region/Elements of the value chains
(I) sSeHcLrUK	H2 Supplier	Production	Chief engineer	10+	500+	UK
(II) sSeHcLrNETH	H2 Supplier	Production	Program manager	10+	500+	Netherland
(III) sEMeHcMrUK	Electrolysers Manufacturer	Support segment	Business development manager	10+	50+	UK
(IV) sSeHcLrUK	H2 Supplier	Production	Chief engineer	10+	500+	UK
(V) sSeHcLrUK	H2 Supplier	Production	Senior energy manager	10+	500+	UK
(VI) sFSeHcLrMEX	Feedstock Supplier (Electricity)	Support segment	Technical process manager	10+	500+	Mexico
(VII) sFCeHcLrUS	H2 Fuel Cell	Utilisation	Vice President of Sales	10+	500+	US
(VIII) sCCSeMcMrUK	CCS Supplier	Support segment	COO	5+	50+	UK
(IX) sSeHcLrFRAN	H2 Supplier	Production	Chairman of the board	10+	500+	France
(X) sFCeHcMrCN	H2 Fuel Cell	Utilisation	CEO	10+	50+	China
(XI) sCeMcSrNRA	Consulting	Policy-oriented support segment	CTO	5+	10+	Nigeria
(XII) sSTeHcLrCN	H2 storage	Storage and distribution	CEO	10+	500+	China
(XIII) sCeMcSrNRA	Consulting	Policy-oriented support segment	CEO	5+	10+	Nigeria
(XIV) sRDeMcLrGER	R&D	Support segment	Scientist	5+	200+	Germany
(XV) sCPeHcMrCN	Complement (Battery/Vehicle)	Support segment	CEO	10+	50+	China
(XVI) sCeHcSrUK	Consulting	Policy-oriented support segment	CEO	10+	10+	UK
(XVII) sFSeMcMrUK	Feedstock Supplier (Electricity)	Support segment	Senior energy manager	5+	50+	UK
(XVIII) sRDSHcLrUK	R&D/H2 Supplier	Production	Supply chain resilience lead	10+	500+	UK
(XIX) sSTeHcLrUK	H2 Storage	Storage and distribution	Hydrogen Business Lead	10+	200+	UK
(XX) sRDSHcLrUK	R&D/H2 Supplier	Production	Business development manager	5+	500+	UK
(XXI) sCeHcLrUK	Consulting	Policy-oriented support segment	Partner	10+	500+	UK
(XXII) sVeHcLrUK	H2 Vehicle	Utilisation	Head of Customer Development	10+	500+	UK
(XXIII) sCeHcMrUK/MLAS	Consulting	Policy-oriented support segment	Chief Technical Officer	10+	50+	UK/Malaysia
(XXIV) sleMcMrCN	Investor	Support segment	CEO	5+	50+	China
(XXV) sFSeMcMr IDSA	Feedstock Supplier (Electricity)	Support segment	COO	5+	50+	Indonesia
(XXVI) sFSeHcLrCN	Feedstock Supplier (Electricity)	Support segment	Senior Manager	10+	500+	China
(XXVII) sSeHcLrCN	H2 Supplier	Production	Hydrogen Business Lead	10+	500+	China
(XXVIII) sVeHcLrCN	H2 Vehicle	Utilisation	Factory Director	10+	500+	China

higher levels extend to influence on the wider ecosystem (ecosystem perspective). Interview feedback refined terminology and added three criteria: technical landscape monitoring, clarity of organisational vision and mission, and operational cost-down targets.

The model's dimensions operate independently, with each level defined by increasing capabilities for assessing supply chain and resilience maturity. Each stage specifies objectives, stakeholder involvement, SCR actions, progress indicators and a maturation path, illustrating how hydrogen companies' resilience develops and which traits enable advancement (Ngai et al. 2013). Indicators

for all criteria are listed in Supplementary Table 1, with supporting quotes in Supplementary Table 2. Given the hydrogen industry's technological immaturity and limited market development (Bag et al. 2025), the MM emphasises production capacity, supply network structure, and operational and maintenance capabilities. Each maturity stage reflects specific HSC characteristics and resilience-building processes. With safety identified by all interviewees as a sector-wide priority, the model is grounded in operations management and technological advancement, supported by case evidence. Resilience development is non-linear, with uneven progress across

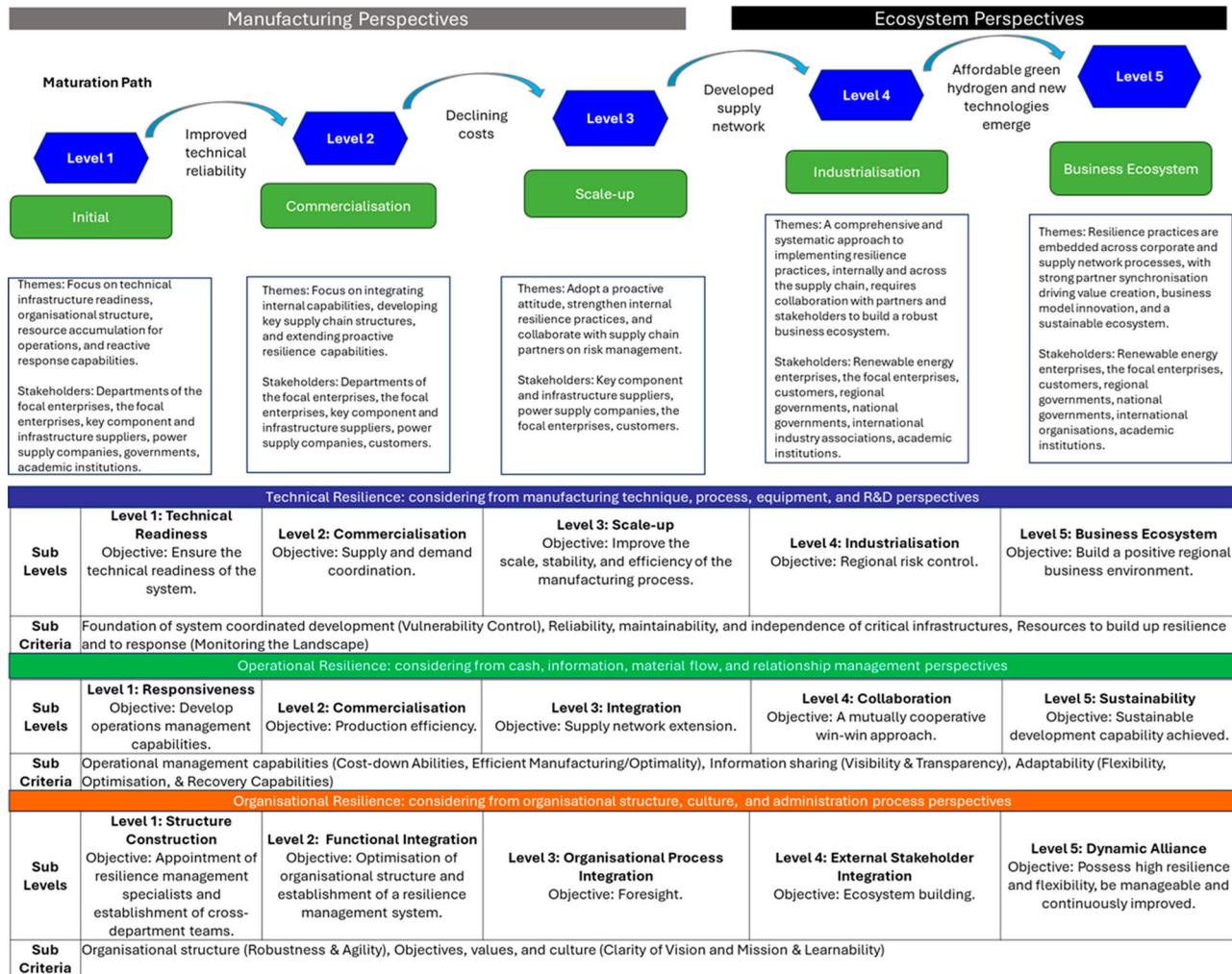


Figure 2. The developed maturity model.

organisational, technical and operational areas. Maturity levels may regress under external shocks, and divergent growth paths can create feedback loops and spin-offs, as discussed in Section 4.4.

Figure 3 shows the dynamic logic of the hydrogen business across organisational, technical and operational dimensions, linking HSCs to upstream/downstream markets and government policy. It clarifies SCR dimensions and inter-organisational ties. The blue line highlights key actions beyond maturity levels 1–2, particularly at Level 3 (Scale-up Stage). Profitability depends on operational efficiency and technical maintenance, with reinvested profits supporting infrastructure, delivery, and market growth (XXVII sSeHcLrCN). Technology investments strengthen supplier reliability and adaptability, while robust infrastructure, resource mobilisation, and IT systems improve stability, transparency and responsiveness to disruption (XXI sCeHcLrUK; XIII sCeMcSrNRA). Organisational learning, collaboration and team resilience further enhance agility and

performance (VIII sCCSeMcMrUK). As hydrogen production expands and specialises, systems shift from reactive to proactive, reducing uncertainty and costs and improving maintenance and risk management. These reinforcing dynamics shape the strategic direction of the Scale-up Stage (Section 4.3), where decentralisation and stronger recovery capabilities enhance resilience and competitiveness.

4.3. Discussion of MM levels

Level-1: This stage marks the industry's early formation, driven by rapid technological progress and a focus on reducing vulnerability. Priorities include infrastructure development and capacity building. Hydrogen production methods face cost and durability challenges (Hassan et al. 2024). Innovation is evident in rising patent activity and research output (XXVI sFSeHcLrCN). Organisations remain in the planning phase, with increasing recruitment and reactive operations focused on timely

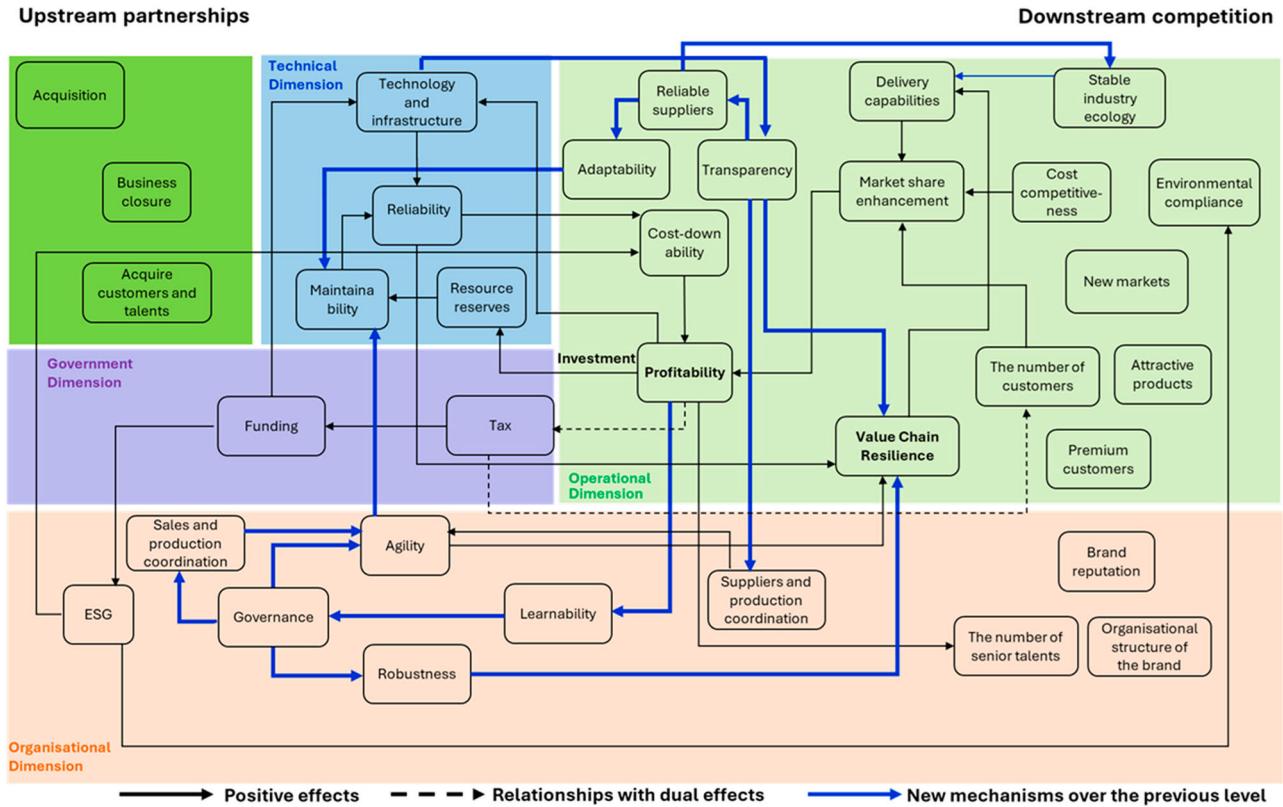


Figure 3. Dynamic relationships across technical, organisational, and operational dimensions show mechanisms at maturity level 3, while unconnected factors reflect expectations for levels 4 and 5.

delivery and inventory turnover (Bueno et al. 2025). Fault management is largely post-event, although early steps towards smarter systems are emerging (XIII sCeM-cSrNRA).

Level-2: At the commercialisation stage, hydrogen products enter the market with a focus on market share and customer value (Alikhani et al. 2025). Technical reliability becomes critical: ‘... the most important is we can trust the technical performance...’ (X sFCeHcM-rCN). Infrastructure scales with demand, supported by preventive maintenance, emergency plans, and insurance. However, ‘maintainability is quite difficult due to its broad scope and limited data on most technologies’ (XII sSTeHcLrCN). As SCRM matures, firms adopt flexible, project-based structures, strengthen emergency response, and shift to more customer-centric, data-driven operations that improve decision-making and reduce waste (Dankyira et al. 2024).

Level-3: This stage scales hydrogen businesses through process standardisation, specialisation, and investment in advanced equipment and management, aiming to boost efficiency, reduce costs, and enable large-scale production. Industries adopt greener technologies, creating a mix of green, renewable and low-carbon hydrogen (Sgarbossa et al. 2023). Recovery protocols and monitoring

systems strengthen resource reallocation and preventive maintenance. A combination of centralised and decentralised controls manages risk and supports integrated operations during commercialisation and expansion (Dankyira et al. 2024).

Level-4: At the industrialisation stage, resilience assessments extend to the wider ecosystem, with external stakeholders and global partners playing key roles (Moktadir and Ren 2024). Sustainable development depends on integrating technology, market forces and organisational dynamics within a strong ecosystem. Industrial clusters reduce risk, foster innovation, and enhance competitiveness (Nikookar, Gligor, and Russo 2024). Advanced systems enable automated, real-time integration of energy and production networks, improving prediction and collaboration. A resilience culture is reinforced through joint training, digitalisation and strong supplier–customer partnerships (De Carolis et al. 2025; Sarkis, Santibanez Gonzalez, and Koh 2019).

Level-5: HSCs demonstrate proactive, adaptive capabilities through continuous planning and reflection. Scaling hydrogen technologies requires policies that prioritise sustainability and innovation (Wood et al. 2023). Fully customer-centric systems integrate operations, data and stakeholder collaboration (Koh, Orzes, and Jia 2019).

Digital twins and high-trust partnerships reduce uncertainty. Sector-wide integration depends on coordination with governments and communities to shape demand and ensure long-term sustainability (Koh et al. 2017). As one interviewee noted, ‘The goal isn’t just sustainability; it is about creating a system that renews itself, reducing waste while adding value’ (XXVII sSeHcLrCN).

4.4. Maturation paths and feedback mechanisms

In the early stages, resilience is largely shaped by external pressures, and an overly narrow internal focus can create inefficiencies or overconfidence (Mohammed, Jabbour, and Diabat 2021). As firms mature, they become better able to respond to, and even shape, their environment. Indicators such as vulnerability control (Supplementary Table 1) capture this shift. Table 3 shows how external pressures trigger adaptive responses through causal loops (see also Supplementary Table 2). For instance, at maturity level 1, unresolved technical issues increase safety risks and undermine trust, which in turn reduces policy support. Firms respond by deploying resilience capabilities to restore reliability and meet policy expectations, progressing from reactive capacity to commercial readiness.

The resilience patterns observed in HSCs align with the emergent behaviours of CASs, as the industry evolves through interaction and learning (Choi, Dooley, and Rungtusanatham 2001; Dolgui and Ivanov 2021; Feizabadi, Gligor, and Choi 2023). Initially, resilience is reactive, exemplified by managing electrolyser supply shortages, yet these actions gradually lead to self-organisation as firms reconfigure networks and form collaborative clusters. As the sector matures, co-evolution among technology, policy, and markets becomes a key resilience driver, with subsidies and carbon pricing stimulating research and development (R&D), improving electrolyser performance, and reinforcing policy support, while diversification and renewable integration help maintain balance amid volatility. Distributed learning and digitalisation through predictive maintenance and digital twins enable faster collective adaptation, while evolutionary change replaces carbon-intensive practices with green hydrogen and promotes circular industrial symbiosis.

Across maturity levels, HSC resilience exhibits progressively advanced features of CASs, evolving from reactive responses toward coordinated network governance and ecosystem-wide co-evolution. The five-level MM demonstrates how resilience capabilities develop through structured transitions. Characteristics such as stronger digital integration, lower performance variance, and faster policy and investment alignment signal tipping points in adaptive capacity, illustrating how micro-level

adaptation scales into macro-level resilience. By identifying modularity and adaptive governance as mediating mechanisms between self-organisation and hierarchy, the MM refines the CAS perspective on distributed control and nested structures within HSCs.

4.5. Fuzzy SWARA results

All interviewees acknowledged the challenges in allocating specific assessment criteria to distinct maturity levels, noting that varying weights and emphases exist across different dimensions. The SWARA analysis is limited by an overrepresentation of experts from the upstream and support segments. Nevertheless, fuzzy SWARA remains an efficient tool for ranking criteria in expert-driven, qualitative contexts like sustainability and resilience (Cui, Wu, and Dai 2021). Unlike Analytic Hierarchy Process (AHP) or Analytic Network Process (ANP), it avoids complex pairwise comparisons and transitivity checks (Ighravwe and Mashao 2023). Its low data requirements and ability to handle ambiguity make it well-suited for emerging sectors such as hydrogen. Improved Fuzzy SWARA (IMF SWARA) was not used, as its complexity and focus on issues like equal weighting and low influence of final rankings were not relevant to this study (Stević et al. 2022).

Experts ranked the three key HSC dimensions to assess their importance in the hydrogen sector. They assigned fuzzy importance values between consecutive criteria, which were aggregated and weighted using fuzzy SWARA. The resulting weights were then defuzzified into crisp values, and an ordinal consistency check ensured alignment between rankings and final weights (Stević et al. 2022).

The steps of the fuzzy SWARA approach followed in this study are:

Step 1: Collect fuzzy relative importance judgements for the criteria ($j, j = 1, 2, 3 \dots n$).

A panel of 28 experts in HSC resilience ranked 13 indicators across three resilience dimensions: technical (5 indicators), operational (4), and organisational (4). The indicators ‘monitoring the landscape’ and ‘cost-down targets’ were assessed by 21 and 27 experts respectively, as they were introduced by participants during the interview iterations. Experts first ranked indicators within each category, then provided an overall ranking across all dimensions. Using a fuzzy comparison scale (Table 4), they assessed each indicator’s importance relative to the highest-ranked one, assigning fuzzy values. Triangular fuzzy numbers (TFNs) were applied to capture uncertainty and subjectivity in expert judgements. The TFNs were calibrated following established fuzzy decision-making frameworks (Garg and Rani 2022) to

Table 3. Selected adaptive feedback loops in maturity progression.

Causal Loops	Quotes
<p>Level 1</p> <p>Reinforcing Loop 1: Government subsidies↑ → Increased corporate R&D investment↑ → Improved technology maturity↑ → Enhanced safety in hydrogen systems↑ → Increased market acceptance↑ → Policy continuity↑</p> <p>Reinforcing Loop 2: Investment in infrastructure↑ → Improved user convenience↑ → Higher sales of hydrogen products↑ → Economies of scale↑ → Increased profitability of hydrogen systems↑ → R&D investment↑</p> <p>Balancing Loop 1: Technological bottlenecks unresolved↑ → Increased probability of safety failures↑ → Public trust↓ → Policy support↓</p>	<p>"... probably using government funding and public sector funding to help develop products that are technologically capable, or using private sector R&D funding to take that risk to develop a product and then move that into a commercial offering.' (V sSeHcLrUK)</p> <p>'... an electrolyser produces green hydrogen ... would be stored in some kind of storage tank ... or transmitted via a pipeline ... to the final consumer ... it could be like a hydrogen fuel cell in a vehicle ... ' (I sSeHcLrUK)</p> <p>"... some of the big gas consumers move over to hydrogen, they can take the brunt of the infrastructure cost because they will take so much hydrogen ... ' (V sSeHcLrUK)</p> <p>"... an excellent case study in the shape of ... they have failed to scale up their manufacturing operations to be able to deliver their product in time ... a massive drop in their share price ... their reputation has taken quite a hit.' (I sSeHcLrUK)</p>
<p>Level 2</p> <p>Reinforcement Loop 3: Government subsidies↑ → Increased R&D investment↑ → Improved technological reserves↑ → Increased electrolyser performance↑ → Lower green hydrogen costs↑ → Increased green hydrogen profitability↑ → Expanded green hydrogen production capacity↑</p> <p>Balancing Loop 2: Trade embargoes↑ → Depletion of critical material stockpiles↑ → Higher green hydrogen costs↑ → Green hydrogen profitability↓ → Green hydrogen output↓ → Market share↓ → Weakened profitability↓</p>	<p>"They may lack some refinements in technology that may make them affordable, suitable for several scales from small companies to big companies ... a logic evolution of any industry ... ' (VI sFSeHcLrMEX)</p> <p>"... when we plan our factories, we may consider the geopolitics tension. And the pandemic, if the companies have their own backup, enough backup, then they may ensure the last level of disruption.' (XXII sVeHcLrUK)</p>
<p>Level 3</p> <p>Reinforcement Loop 4: Scale-up of manufacturing capacity↑ → Increased profits↑ → Greater investment in infrastructure↑ → Enhanced reliability↑ → Improved HSC resilience↑ → Increased delivery capability↑ → Expanded market share↑ → Strengthened profitability↑</p> <p>Balancing Loop 3: Lower fossil fuel prices↑ → Cost advantage of green hydrogen↓ → Market share↓ → Profitability↓ → Investment appeal↓ → Infrastructure development↓</p>	<p>"... they're going to learn a lot of things from building it, how could they do it better, whatever construction, where they can order the equipment from, and who can supply it cheaper ... ' (VII sFCeHcLrUS)</p> <p>"... the problem with green hydrogen is the cost is considerably higher for it to be economically viable ... like 10, 15 percent ... we can switch, but I think it's like two or three times at least.' (XVIII sRDSeHcLrUK)</p>
<p>Level 4</p> <p>Reinforcement Loop 5: Rising profits↑ → Acquisition of other enterprises↑ → Growth in enterprise scale↑ → Skilled workforce↑ → Organisational governance capabilities↑ → More resilient organisation↑ → Improved logistics capacity↑ → Expansion of market share↑ → Increased profits↑</p> <p>Balancing Loop 4: Growth in enterprise scale↑ → Operational costs↑ → Profitability of green hydrogen↓ → Green hydrogen production capacity↓ → Fulfilment of market demand↓ → Public trust↓ → Profitability↓</p>	<p>"Business ecosystem is really about developing the industrial scale systems ... they become more and more commercially viable so you take advantage of economies of scale ... ' (XXV sFSeMcMr IDSA)</p> <p>'... we're still finding scale up because we're still trying to understand how things work ... it's kind of hard-to-find experts who understand what's going on.' (XVII sFSeMcMrUK)</p> <p>"... one of the key features of the sector at the moment, is how to transition from low-rate to high-rate manufacturing.' (XXII sVeHcLrUK)</p> <p>"... learnability, I think that's an interesting phrase because I think one of the keys to resilience organisationally is to be able to recognise what phase of development your organisation is.' (I sSeHcLrUK)</p>
<p>Level 5</p> <p>Reinforcement Loop 6: Rising profits↑ → Increased investment in ESG↑ → Enhanced environmental compliance↑ → Product innovation and improvement↑ → Greener industrial ecosystems↑ → Customer satisfaction↑ → Profitability↑</p> <p>Balancing Loop 5: New technological alternatives↑ → Hydrogen market penetration↓ → Green hydrogen profitability↓ → Green hydrogen production capacity↓ → Customer satisfaction↓ → Policy support↓ → Shift towards a new ecosystem↑</p>	<p>'... Maybe you should look at these three models of these three areas of sustainability. Has it taken care of environmental concerns? Has it taken care of social welfare of the people who benefit employees or the host communities and all of that? ... is it also able to empower the company in terms of generating finances?' (XIII sCeMcSrNRA)</p> <p>'The goal isn't just sustainability; it is about creating a system that renews itself, reducing waste while adding value' (XXVII sSeHcLrCN)</p>

Table 4. Linguistic terms for relative importance judgements.

Category for 5 indicators	Fuzzy Value (TFN)	Interpretation
1–No Importance	(0, 0, 0.25)	No importance; at most minimal relevance
2–Low Importance	(0, 0.25, 0.5)	Low importance; only weak alignment
3–Moderate Importance	(0.25, 0.5, 0.75)	Moderate match
4–Importance	(0.5, 0.75, 1)	Strong match with minor imperfections
5–High Importance	(0.75, 1, 1)	Very high confidence in importance
Category for 4 indicators	Fuzzy Value (TFN)	Interpretation
1–No Importance	(0, 0, 0.25)	No importance; at most minimal relevance
2–Low Importance	(0.25, 0.5, 0.75)	Low importance; only weak alignment
3–Moderate Importance	(0.5, 0.75, 1)	Moderate match
4–High Importance	(0.75, 1, 1)	Very high confidence in importance
Category for 3 indicators	Fuzzy Value (TFN)	Interpretation
1–Low Importance	(0, 0.25, 0.5)	Low importance; only weak alignment
2–Moderate Importance	(0.25, 0.5, 0.75)	Moderate match
3–High Importance	(0.5, 0.75, 1)	Very high confidence in importance

maintain consistency and moderate fuzziness. Linguistic terms were converted into TFNs in accordance with prior resilience and sustainability studies (Kuzu 2023). The process was iterative, allowing refinement of judgments (Cui, Wu, and Dai 2021).

Step 2 Calculate the aggregated average values (S_j) of the experts' evaluations for each criterion.

Combine the relative importance ratings of the criteria using equation (1). Cui, Wu, and Dai (2023) refer to this ratio as the comparative significance of the S_j value.

$$S_j = \left(\frac{\sum_1^n l_j}{n}, \frac{\sum_1^n m_j}{n}, \frac{\sum_1^n u_j}{n} \right) \quad (1)$$

where (l_j, m_j, u_j) is a TFN.

Step 3: Compute the coefficient value (K_j), recalculated fuzzy weights (Q_j) and relative weighting (W_j) of criteria by expressions (2)–(4).

$$K_j = 1 + S_j \quad (2)$$

where K_j represents criterion j 's co-efficient and S_j means criterion j 's relative importance.

$$Q_j = \frac{Q_{j-1}}{K_j} \quad (3)$$

where Q_j means the initial weights for criterion j .

$$W_j = \frac{Q_j}{\sum_1^n Q_j} \quad (4)$$

where W_j represents the criterion's j importance.

Kendall's W results show strong expert agreement, with an overall concordance coefficient of 0.6582 for the three main criteria (Hashemkhani Zolfani, Yazdani, and Zavadskas 2018). Among the sub-dimensions, technical ($W = 0.6514$) and organisational resilience ($W = 0.6571$) display similar consistency, while operational resilience ($W = 0.568$) indicates moderate agreement, reflecting slightly greater variability in expert judgement. Sensitivity analysis tested the stability of the weights by reducing each criterion's weight by 10% (Bouraima et al. 2023). Modified TFNs were also applied by widening the lower (l) and upper (u) bounds by 10% while keeping the peak value (m) constant. In all cases, the ranking order of weights remained unchanged, confirming the robustness of the results. The results confirm ordinal consistency, and reliability tests validate the expert panel's judgments. Detailed calculations are provided in Supplementary Information 3, and the interview questions in Supplementary Information 4.

The final weighted results for each indicator are presented in Table 5. Technical reliability is identified as the most important within the technical dimension. In the organisational dimension, clarity of vision and mission holds the highest priority, while efficient manufacturing emerges as the most critical sub-criterion in the operational dimension. These findings contrast with Kazançoglu et al. (2022), who ranked supply chain visibility highest for the first tier. However, they align with Shah et al. (2025), who identified cluster-based development (efficient manufacturing) as a key enabler. This divergence likely reflects the hydrogen sector's early-stage

Table 5. Results of weighted indicators based on fuzzy SWARA.

Technical Criteria	Comparative Importance of Average Value S_j	Coefficient K_j	Recalculated Weight Q_j	Weight W_j	Crisp Weight
Technical Reliability	–	(1, 1, 1)	(1, 1, 1)	(0.247, 0.343, 0.425)	0.31
Monitoring the Landscape	(0.25, 0.5, 0.75)	(1.25, 1.5, 1.75)	(0.571, 0.666, 0.8)	(0.141, 0.229, 0.340)	0.22
Technical Independence	(0, 0.25, 0.5)	(1, 1.25, 1.5)	(0.380, 0.533, 0.8)	(0.094, 0.183, 0.340)	0.19
Vulnerability Control	(0, 0.25, 0.5)	(1, 1.25, 1.5)	(0.253, 0.426, 0.8)	(0.062, 0.146, 0.340)	0.17
Maintainability	(0.25, 0.5, 0.75)	(1.25, 1.5, 1.75)	(0.145, 0.284, 0.640)	(0.035, 0.097, 0.272)	0.12
Organisational Criteria					
Clarity of Vision/Mission	–	(1, 1, 1)	(1, 1, 1)	(0.319, 0.368, 0.443)	0.36
Learnability/Life-cycle	(0.25, 0.5, 0.75)	(1.25, 1.5, 1.75)	(0.571, 0.667, 0.8)	(0.182, 0.245, 0.354)	0.25
Robustness	(0, 0.25, 0.5)	(1, 1.25, 1.5)	(0.457, 0.667, 0.8)	(0.145, 0.245, 0.354)	0.24
Agility	(0.5, 0.75, 1)	(1.5, 1.75, 2)	(0.228, 0.381, 0.533)	(0.072, 0.140, 0.236)	0.14
Operational Criteria					
Efficient Manufacturing	–	(1, 1, 1)	(1, 1, 1)	(0.338, 0.415, 0.479)	0.4
Cost-down Targets	(0.25, 0.5, 0.75)	(1.25, 1.5, 1.75)	(0.571, 0.667, 0.8)	(0.193, 0.276, 0.383)	0.27
Adaptability	(0.25, 0.5, 0.75)	(1.25, 1.5, 1.75)	(0.326, 0.444, 0.64)	(0.110, 0.184, 0.306)	0.19
Transparency	(0.25, 0.5, 0.75)	(1.25, 1.5, 1.75)	(0.186, 0.296, 0.512)	(0.063, 0.123, 0.245)	0.14
Three Dimensions					
Technical	–	(1, 1, 1)	(1, 1, 1)	(0.375, 0.443, 0.5)	0.43
Operational	(0, 0.25, 0.5)	(1, 1.25, 1.5)	(0.667, 0.8, 1)	(0.25, 0.3544, 0.5)	0.36
Organisational	(0.5, 0.75, 1)	(1.5, 1.75, 2)	(0.333, 0.457, 0.667)	(0.125, 0.202, 0.333)	0.21

development, where safety and technical reliability take precedence over visibility due to an immature supply network.

The MM assesses resilience across three dimensions: Technical, Operational, and Organisational. Each includes sub-practices rated on a 5-point Likert scale (1 = Not implemented, 5 = Fully implemented) (Correia, Garrido-Azevedo, and Carvalho 2023). Since resilience strategies rarely fit fixed levels, maturity is measured by depth of implementation. Sub-dimension scores (e.g. Organisational Resilience) are calculated as weighted averages of their criteria (e.g. Robustness, Agility), and overall HSC maturity is the weighted average of the three main dimensions. Progression requires embedding more advanced practices and maintaining balanced growth across dimensions.

5. Application of the MM

The MM was initially evaluated by two senior managers from hydrogen-related firms, one supplying hydrogen energy and the other producing hydrogen-based direct reduced iron (H-DRI), each with over 500 employees. Using a questionnaire adapted from Correia, Garrido-Azevedo, and Carvalho (2023), they assessed the MM's relevance, comprehensiveness, mutual exclusivity, clarity of maturity levels, ease of understanding, and practicality. Both experts found the MM comprehensive and well-suited for HSC resilience, confirming the relevance and accuracy of its dimensions and maturity levels. One noted potential subjectivity in terms like 'implemented

but not fully embedded,' leading to the addition of clarifying examples (see Table 6). Another raised usability concerns, suggesting the model's breadth might hinder efficient data collection. Digital visualisation tools were recommended to improve usability.

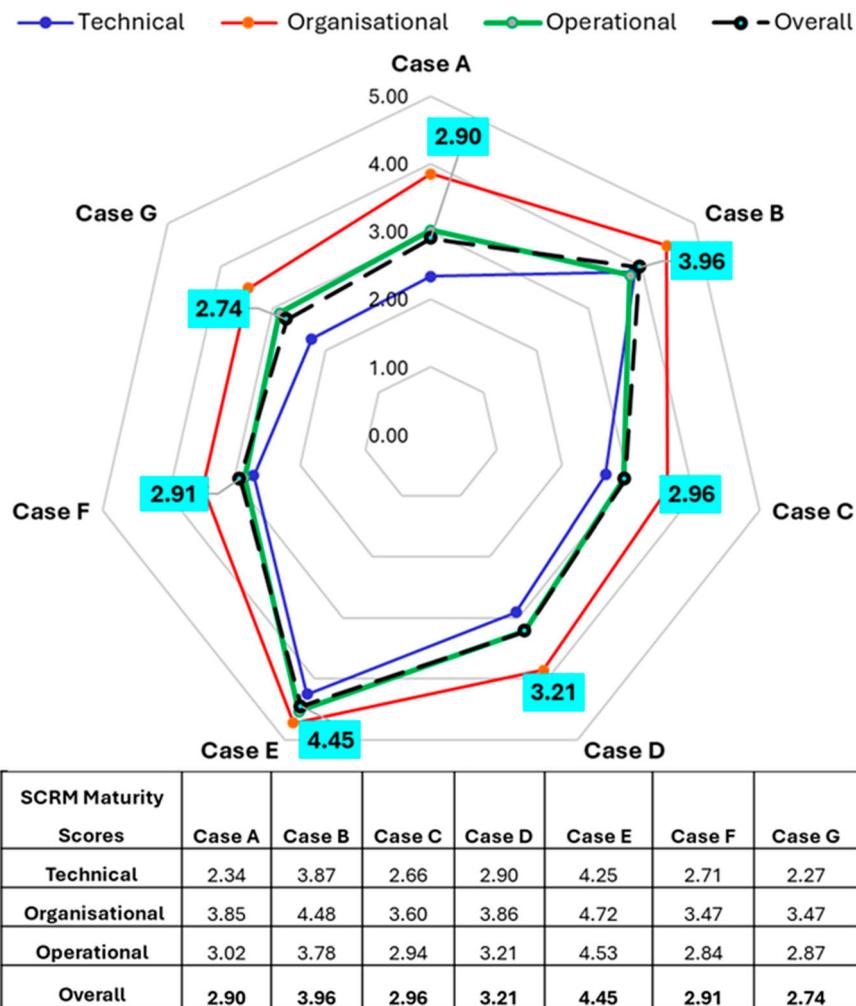
5.1. Exploratory case studies

Seven exploratory case studies were conducted across different segments of the HSCs, covering upstream electricity feedstock and hydrogen production as well as downstream applications including mobility and fuel cell deployment. Cases were selected using a purposeful sampling strategy to ensure diversity in both organisational types and geographical regions. The cases covered state-owned, private, and publicly listed enterprises, and spanned multiple regions, including China, France, the United Kingdom, Africa, and Indonesia. This cross-regional selection enabled the identification of patterns or divergences shaped by local contexts. The sample size was guided by theoretical saturation, ensuring comprehensive insights while maintaining analytical depth. The results demonstrate the model's effectiveness in capturing different levels of resilience capability across diverse industrial contexts. Details of the case companies and interview participants are provided in Table 7. The evaluation results are present in Figure 4.

Case A, a state-owned Chinese automaker specialising in hydrogen heavy-duty trucks, has over 500 employees and 50 years of experience. Positioned at the vehicle utilisation stage, it relies on external partners for hydrogen supply. With a maturity score of 2.90 (Figure 4), it

Table 6. Sample illustration of the indicators.**Criteria:** Technical Resilience

Sub Criteria: Foundation of system coordinated development (Vulnerability Control)

Strategy: "Hazard identification, risk assessment, weakness identification, and penetration testing to identify potential vulnerabilities."**Rating on the 5-Point Likert Scale:****(1):** Not implemented; the organisation has no formal processes or tools for hazard identification or penetration testing.**(2):** Partially implemented; some ad hoc efforts are made to identify risks and vulnerabilities, but these are inconsistent and lack formal structure or documentation.**(3):** Moderately implemented; the organisation has processes for hazard and risk assessment, but implementation is limited, with periodic rather than continuous coverage. Penetration testing is done but not applied systematically across all systems.**(4):** Well-implemented; comprehensive, systematic hazard identification and risk assessment processes are in place, with routine penetration testing. Results are documented and actively inform decision-making and continuous improvement.**(5):** Fully implemented; hazard identification, risk assessment, and penetration testing are fully integrated into operations, covering all critical areas. Continuous monitoring and adaptive improvements enable proactive vulnerability management.**Figure 4.** Exploratory case study results.

has reached commercialisation but not scale-up. It shows strong operational and organisational resilience but faces challenges from supplier dependence and limited technical independence. Despite a flexible job-shop model, its large size limits agility. Policy support exists, but limited infrastructure and supplier reliance hinder growth.

Case B, a Chinese green hydrogen producer for industrial decarbonisation, scored overall (3.96), especially higher in organisational (4.48) and technical (3.87) resilience, highlighting upstream firms' strength in coordination and resilience-building. Case C, a private Chinese hydrogen fuel cell company for mobility and stationary uses,

Table 7. Overview of case companies and participants.

Case study	Layer of the HSC	Ownership structure	Participants	Locations
Case study A	Hydrogen truck	State-owned enterprises	Chief factory manager, technical director, operations control manager	China
Case study B	Hydrogen supply	State-owned enterprises	Business development manager, hydrogen business lead, operations director	China
Case study C	H2 fuel cell	Privately held enterprises	CEO and technical director	China
Case study D	Feedstock supplier (electricity)	Subsidiary of a public-limited company	CEO and chief technical officer	Africa
Case study E	HSCs	Publicly owned company	Chairman of the board and a project manager	France
Case study F	Hydrogen storage	Privately held enterprises	Chief technical officer and founder	UK
Case study G	Feedstock supplier (electricity)	State-owned enterprises	Operations advisor and officer of production management	Indonesia

scored moderately (2.96). It has niche technical strengths but struggles with scaling and broader supply chain integration.

Case D, an African subsidiary of a publicly listed energy firm, provides renewable electricity to hydrogen production. Its score of 3.21, driven by strong organisational (3.86) and operational (3.21) aspects, suggests renewables sectors can support HSC resilience through more mature operations and infrastructure management experience. Similarly, Case E, a global French industrial gas company, leads with the highest maturity (4.45), reflecting technical strength (4.25), robust organisation (4.72), and advanced operations (4.53). The interviewee noted: ‘As a century-old enterprise, we can always recover quickly in a crisis.’ Its vertical integration supports balanced and mature resilience.

Case F, a UK-based liquid hydrogen storage company, scored relatively low overall (2.91), particularly in technical resilience (2.71). Despite active industry involvement and specialised knowledge, its narrow technological focus and lack of supply chain integration limit its resilience. Similarly, Case G, a state-owned solar PV enterprise, recorded the lowest overall score (2.74). Although its renewable technologies could support a hydrogen hub, Case G’s low technical (2.27) and operational (2.87) scores indicate an early-stage position in the hydrogen value chain. Interview evidence reveals deeper structural and contextual barriers. The interviewee noted that ‘the regulation is not that supportive yet... they keep thinking about changing the regulations’, reflecting policy instability that limits capability development. Frequent changes to export–import rules and capacity limits were described as ‘a major disruption that most other players face,’ while ‘local solar modules compete with international products,’ exposing firms to market pressures. These uncertainties constrain planning and adaptation, leaving the firm ‘working in an unfair space.’ This case highlights the need for consistent policy support and

protective quotas to strengthen local firms in the early stages of hydrogen development.

5.2. Cross-case comparison

A comparison of upstream and downstream segments reveals distinct differences in resilience maturity. Upstream actors such as Case B and Case D, involved in electricity or hydrogen production, show higher operational maturity due to established infrastructure and experience. However, their resilience remains limited by uncertain downstream demand. As noted by a Case D interviewee, ‘I wouldn’t say we’ve actually captured a larger share of the hydrogen market here in ...’ Case G illustrates that scalability is hindered without a reliable market and supportive environment. As one interviewee stated, ‘regulatory risk or market risk... a way to prevent that risk should come first...’ In contrast, downstream firms including Case A with hydrogen trucks, Case C with fuel cells, and Case F with aerospace storage show lower overall maturity than Cases B and D. These firms face challenges such as evolving customer demand and limited infrastructure, reflecting the early stage of hydrogen application markets. The strong performance of Case E highlights the value of vertical integration across the value chain, demonstrating that supply network integration supports more balanced and robust resilience.

The cross-case comparison reveals clear differences in resilience maturity across firms and value-chain positions. Mapping maturity levels to actionable improvements demonstrates how the model converts assessment results into development pathways. Early-stage firms (Levels 1–2: Cases G, A, C, F) require stronger technical readiness, infrastructure, and capability building. Their dependence on external partners and weak coordination highlight the need for supplier diversification, digital integration, and targeted R&D, supported by subsidies and early transformation policies. Intermediate firms

(Level 3: Cases B, D) show higher system integration and adaptive management, focusing on data coordination and cross-sector partnerships. At advanced stages (Levels 4–5: Case E), system resilience becomes network-oriented, characterised by predictive management, continuous improvement, and ecosystem-wide collaboration, supported by market incentives that drive innovation and decarbonisation.

The cases show that high resilience capability scores do not guarantee resilience progression, as actual performance depends on market conditions, environmental barriers, and policy uncertainty. For example, Case B scores well but relies on downstream demand to improve resilience. These findings highlight the hydrogen sector's interdependent and evolving nature, emphasising the need for cross-sectoral coordination. The case studies confirm the MM's practical value in assessing HSC resilience. The findings from Case G align with those of Permana, Handoko, and Gomonov (2025), while the findings from Case E reflect the industrialisation level observed by Bag et al. (2025), further demonstrating the model's practicality. While further validation is needed, its grounding in literature and expert input supports continued development and application.

6. Discussion

This study develops a novel framework to evaluate HSC resilience maturity, extending SCRM models with HSC-specific criteria and system-level integration. The MM captures dynamic interactions within hydrogen production and its value chain, offering a systematic way to analyse resilience capabilities across maturity stages while accounting for regulatory and market contexts, addressing research question one. It supports industry-wide benchmarking across diverse national settings, validated through seven case studies, addressing research question two. The MM outlines progression from manufacturing resilience at lower levels (1–3), focused on disruption resistance and recovery, to ecological resilience at higher levels (4–5), emphasising external networks, sustainability, and adaptive capacity. The model helps firms navigate globalisation and Industry 4.0. As hydrogen's role in sustainability grows, it offers guidance to close resilience gaps under shifting policies and markets.

Unlike existing models that target established sectors or remain conceptual (Bueno et al. 2025; Fornasiero et al. 2024; Guerra et al. 2024; SMR 2017), this MM specifically addresses HSC resilience needs, including hazard management, sustainable production, and market adaptability via a stepwise framework. Unlike Mendes, Leal, and Thomé (2016), which ends at 'optimised demand-driven' maturity, this model uses a CAS lens to reflect

long-term ecosystem evolution, prioritising sustainability and renewable transitions. Aligned with IEA (2025)'s concept of technological maturity as widespread deployment with incremental innovation, it extends maturity to organisational and operational domains, reflecting the non-linear nature of supply chain resilience. Exploratory case studies show the model's effectiveness in identifying resilience levels and guiding progression. Grounded in a strong SCRM foundation, the MM's dimensions may be applicable to other emerging, sustainability-focused industries (Table 8).

6.1. Implications for research

This study traces SCRM's evolution from reactive recovery to proactive adaptation, reflecting ecological resilience. The MM elaborates CAS principles by evaluating adaptability, learnability, and responsiveness, distinguishing early internal resilience (Levels 1–3) from ecological resilience (Levels 4–5) to clarify system boundaries and improve CAS's predictive power in hydrogen contexts. Unlike Cynefin, which supports short-term responses by categorising problems but lacks guidance for long-term, systemic improvement, this MM contributes to CAS theory by clarifying industry development boundaries and guiding continuous resilience enhancement in the hydrogen sector (Nachbagauer 2021).

The MM does not explicitly account for firm size or age, though both influence resilience. Larger firms tend to handle disruptions better due to greater resources, and older firms benefit from accumulated experience (Parast and Golmohammadi 2022). The model assumes a general progression from smaller, reactive firms to larger, proactive ones. Interviewees confirmed this: startups report frequent disruptions, while established firms experience fewer, linking organisational maturity to resilience. While MMs often associate higher maturity with better financial performance (de Andrade, Gusmão, and Silva 2021), this MM emphasises resilience as a developmental goal. Maturity level 1 focuses on infrastructure and reliability, with profitability becoming crucial during commercialisation and scale-up. During levels 4 and 5, reliability and profitability are established, shifting the focus to green development and new applications. The MM measures progress through resilience capabilities and defines sustainable growth aligned with societal needs as the highest maturity level.

Limitations of this study include qualitative approach, expert reliance, and focus on specific HSC contexts limit the generalisability of its findings. The small sample and early-stage market focus restrict applicability to mature or diverse markets. Although this work

Table 8. Comparisons to other MMs.

Aspect	(Goncalves Filho, Andrade, and Marinho 2010)	(Ngai et al. 2013)	(Mendes, Leal, and Thomé 2016)	(SMR 2017)	(Asah-Kissiedu et al. 2021)	(Henriquez, Muñoz-Villamizar, and Santos 2023)	(Fornasiero et al. 2024)	(Dunzer et al. 2025)	(Bueno et al. 2025)	Novelty of this work
Scope and context	Safety culture in Brazilian oil and gas organisations	Environmental sustainability in manufacturing, energy and utility resource management	Global consumer packaged goods company in the beverage industry operating in Brazil, the United States, and Uruguay.	Resilience building process of European cities Urban management	An integrated SHE (Safety, Health, and Environment) capability MM for the construction sector.	Operational excellence tailored to businesses in Colombia Multiple sectors	AI and big data applied across Europe's process industries, including chemicals, steel, cement, ceramics, water, and engineering.	Process mining capabilities in manufacturing and logistics technology applications	Smart shop floor control (Industry 4.0)	Addresses HSC-specific challenges, using resilience indicators tailored to HSC management and industrial transition. It introduces resilience capabilities as measurable constructs specific to HSCs
Theoretical foundation	Safety culture model; IAEA's three-stage safety culture development model	Capability Maturity Model Integration (CMMI) in a staged representation	Demand-driven supply chain concepts; push-pull systems; contingency Theory	Contemporary theories in resilience engineering	CMMI concepts	Natural resource-based view; institutional theory-based view; CMMI	Organisational and human factors; industry 4.0 and digital transformation	Maier, Moultrie, and Clarkson (2011)'s technology-focused MM	Socio-technical systems theory	Grounded in CAS theory, this is a novel model to clarify hydrogen industry development stages and inform future capacity building through resilience capability and causal loop analysis.
Constructs and levels	5-level MM: 1 – Pathological, 2 – Reactive, 3 – Bureaucratic, 4 – Proactive and 5 – Sustainable	5-level MM: Initial (ad hoc processes); Managed (requirements and control); Defined (standardised processes); Quantitatively Managed (data-driven performance); Optimising (continuous improvement)	5-level MM: Basic Push Operation; Optimised Push; Hybrid Push-Pull; Advanced Demand-Driven (Pull); Optimised Demand-Driven (Pull)	5-level MM: Starting, Moderate, Advanced, Robust, and Vertebrate	A 5-level continuous capability MM	5-level MM: 1- Basic Level, 2- Beginner Level, 3- Training Level, 4- Innovative Level, 5- Champion Level	4-level model: Level 1: No AI/BD use; low awareness; Level 2: Limited experimentation; Level 3: Active implementation with impact; Level 4: Full adoption and optimisation; AI/BD is integral.	5 maturity levels for each focus areas	5-level MM: Level1 Non-existent, Level2-Digitalised, Level3-Integrated, Level4 Automated, Level5-Smart	Distinguishes between manufacturing resilience (Levels 1–3: resistance and recovery) and ecological resilience (Levels 4–5: external network development and sustainability) evaluates resilience across production systems, HSC networks, and the broader hydrogen ecosystem. It contributes to CAS theory by breaking down system-level resilience into a measurable set of agent-level capabilities, providing a framework to empirically assess a system's adaptive capacity. Although currently focused on HSCs, the model applies triangulated validation using literature synthesis, industry case comparisons, and expert judgment.
Validation	Validated by 23 Brazilian and multinational petrochemical companies	A case study of a Chinese textile manufacturing company based on a one-month observation	A case study in the beverage sector across Brazil, the United States, and Uruguay	Delphi-validated across cities, strategic but requires local tailoring.	Validated in a Ghanaian construction firm and a survey of 15 professionals, reflecting local safety, health and environmental practices.	Validated via expert interviews in 49 Colombian companies	Validated with 30 companies and two industry workshops	Systematic case-study review and 12 semi-structured interviews with logistics experts	Case study with four managers in a Brazilian steel manufacturer	

illustrates maturation progression through causal mechanisms across levels, additional causal relationships between variables in the MM may emerge under specific scenarios and contexts. Although theoretically sound, the MM's empirical testing covers only seven cases, requiring further validation of its assumptions (Gökalp and Martinez 2021).

6.2. Implications for practice

This MM combines descriptive and comparative methods to assess resilience levels and enable benchmarking in the hydrogen industry. The MM offers insight into a firm's position and guides targeted improvements, including how to respond to hydrogen-sector risks such as high energy and water demands and hydrogen leakage, which require better regulation and support for renewable energy communities (Kyriakopoulos and Aravossis 2023).

Government subsidies can support growth but also risk creating dependency and weakening technical independence and adaptability (Robinson et al. 2023). The MM captures this through technical independence, adaptability and organisational learnability. Interviewees recognised the value of supportive policies but warned of their risks in immature hydrogen markets. Case G shows how policy instability and shifting support schemes amplify uncertainty and undermine long-term capability building, emphasising the need for a consistent, predictable regulatory framework with stable export–import rules and clear protective measures such as quotas. Overall, policies should balance short-term support with long-term sustainability, requiring strategic patience and commitment (Li et al. 2023).

7. Conclusion

This study presents an MM based on CAS theory and tailored to hydrogen, guiding resilience and responsiveness improvements. The case study reveals that supply network integration enhances HSC resilience. Hydrogen companies can use the MM to identify gaps in their resilience capabilities and improve readiness for proactive, sustainable HSCs. As derived from the cross-case comparison, policy recommendations include phased support: R&D and infrastructure building subsidies at early stages (maturity level ≤ 1), supply chain transformation quotas during commercialisation and scale-up (maturity level 2 and 3), and market-based incentives for decarbonisation in more mature phases (level ≥ 3).

The proposed MM is specific to the emerging hydrogen industry. As the sector remains technologically immature and policy-fragmented, its resilience indicators and development pathways may evolve with

future advancements and market stability. Periodic revalidation and application to other renewable sectors are therefore recommended. The expert sample, reflecting the early-stage nature of the industry and dominated by upstream stakeholders, may bias results toward production concerns while underrepresenting downstream and organisational views. Emphasis on technical and operational factors may also overlook broader organisational aspects of value chain resilience. Although fuzzy SWARA reduced uncertainty, it could not fully address this imbalance, highlighting the need for more diverse expertise as the industry matures. Case study validation was constrained by limited size and diversity, with contextual variables such as firm size and regulation affecting outcomes. Broader testing across varied hydrogen companies is needed to verify assumptions and enhance the model's applicability. Additionally, future research could examine sustainability and market maturity to provide a more comprehensive view of sector development. This would help establish standards for assessing the MM's quality and practical value in emerging sectors.

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people • buildings • city.

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Data availability statement

The data that support the findings of this study are available from the corresponding author, [LK], upon reasonable request.

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