

## Article

# Exploring the Future of Manufacturing: An Analysis of Industry 5.0's Priorities and Perspectives

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## Abstract

The present study explores the enablers for the integration of Industry 5.0 principles within the automotive industry, emphasizing the transition towards human-centric, sustainable, and resilient manufacturing. This research utilized a three-round Delphi method involving a panel of experts to identify, evaluate, and prioritize key enablers associated with the adoption of Industry 5.0. In order to enhance the analytical depth, consensus trajectory mapping was employed to track opinion convergence across rounds. Fuzzy ranking was applied to provide a more nuanced evaluation of item prioritization. The results indicate a substantial degree of consensus on subjects such as collaborative robotics, cognitive automation, and circular manufacturing. The present study offers theoretical and practical implications, providing a roadmap for researchers and automotive stakeholders seeking to operationalize Industry 5.0 values.

**Keywords:** automotive manufacturing; consensus trajectory mapping; Delphi method; fuzzy ranking; industry 5.0



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## 1. Introduction

The movement from Industry 4.0 to Industry 5.0 signifies a change in manufacturing thinking, shifting from an industrial system dominated by automation to a coupled system centered on human factors, sustainability, and resilience [1,2]. In the automotive sector, which is a global, resource-limited, and rapidly evolving technological landscape, Industry 5.0 presents a compelling opportunity to find the balance between efficiency and values associated with human and environmental resource use [2–4]. While Industry 4.0 focused on the digital transformation of industry, Industry 5.0 is also focused on developing human creativity in concert with intelligent systems. The foundational pillars for Industry 5.0 include human-centricity, sustainability, and resilience with concepts such as artificial intelligence (AI), internet of things (IoT), digital twins, and collaborative robots (cobots) facilitating this transition [1,5]. Human-centered design means combining the elements of human intelligence, human creativity, and human decision-making with the technologies of the IoT, cobots, and advanced AI, and it brings more inclusivity and adaptability to the manufacturing world. Sustainability means that environmental and social considerations of resource and waste efficiencies, circular economy practices, and carbon footprints together guide industrial development towards achieving global sustainability objectives [6]. Resilience means the anticipation of unforeseen events that disrupt industrial systems, the

absorption of the impact of disruption, and the recovery from that or similar disruptions in the future. Resilience incorporates flexible processes, strong supply chain processes, and digital twins to allow real-time observations and predictive decision-making [6]. The equilibrium of these three pillars forms a dynamic system for human intelligence and expertise to complement and extend advanced technologies to make adaptive systems that efficiently work in organized discussions around the reality and potential of Industry 5.0 [6]. The European Commission formally announced Industry 5.0 in 2021 to highlight its orientation towards creating social and environmental objectives beyond industrial efficiency [7].

The automotive industry is an example of Industry 5.0 in action. Companies are using cobots along with AI-supported decision-making and digital twin systems, collectively creating flexibility and a human-centered production environment [4]. For example, sustainability and ethical considerations were clearly at the forefront of Toyota's introduction of new hydrogen fuel cell designs and cobots [8,9].

At the heart of Industry 5.0 is the beneficial collaboration between human workers and machines. Cobots are increasingly completing dangerous or redundant work more easily in automotive assembly, while workers are engaged in quality control and innovation, increasing safety and job satisfaction. Similar findings have appeared in the more generalized human-focused manufacturing literature, in which worker notions of well-being and creativity improve when automation supports, rather than substitutes, the work of individuals [8,10–12]. Industry 5.0 is closely linked to the circular economy and eco-efficiency. Incorporating circular practices in the automotive manufacturing industry, when combined with lean systems, can increase competitiveness and reduce waste. Moreover, energy-smart factories that utilize renewable energy and IoT-instructed energy grids (e.g., Tesla's net-zero Gigafactory) represent industry-level dedication to low-carbon transformation [1,4,8,13].

The current Industry 5.0 research pertaining to the automotive sector centers around the synergistic integration of human expertise and advanced technologies, like AI, robotics, and digital twins, to achieve hyper-personalization, resilience, and sustainability [14]. Studies highlight the potential for cobots to enhance worker safety and productivity in assembly lines, while simultaneously addressing labor shortages [15]. However, debates persist concerning the optimal balance between automation and human intervention, with some research emphasizing the need for robust training programs to upskill the workforce and mitigate potential job displacement [16]. Another significant area of investigation revolves around data-driven decision-making using digital twins for predictive maintenance and supply chain optimization, leading to reduced downtime and material waste [17]. A critical debate involves the ethical implications of AI-powered systems in autonomous driving and personalized in-car experiences, demanding rigorous ethical guidelines and regulatory frameworks [18]. Moreover, the research is increasingly focusing on circular economy principles, leveraging Industry 5.0 technologies to facilitate the remanufacturing and recycling of automotive components, fostering a more sustainable automotive ecosystem [17,18].

The global Industry 5.0 market size was valued at USD 71.15 billion in 2024 and is projected to rise from USD 93.39 billion in 2025 to approximately USD 987.11 billion by 2034, exhibiting a compound annual growth rate (CAGR) of 30.08% from 2025 to 2034 [19]. The industry 5.0 market is driven by the growing need for large-scale customization [19]. The growth of the Industry 5.0 market is driven by the increased adoption of new technologies, such as AI, IoT, robotics, and blockchain, which improve productivity and operational efficiency. The adoption of Industry 5.0 measures to reduce risks and disruptions is becoming increasingly rapid, as evidenced by the greater emphasis placed on resilience, agility, and flexibility in supply chains and manufacturing processes in the post-pandemic era. In 2024, it was determined that the European Industry 5.0 market represented a lucrative region, distinguished by its pronounced emphasis on sustainability, collaborative workforce practices,

and smart manufacturing methodologies [19,20]. The European Union's strategic policies promote the adoption of AI-driven automation, circular economy practices, and digital transformation across a range of industries, including the automotive and aerospace sectors. The increased investment in the research and development in cyber-physical systems and the IoT is driving the next phase of manufacturing evolution [19,20]. The Industry 5.0 market in the Asia-Pacific region is expected to grow at a CAGR of over 31% from 2025 to 2030 [20]. The People's Republic of China is at the vanguard of Industry 5.0 adoption, with considerable investments in robotics, artificial intelligence, and smart manufacturing technologies. The government's "Made in China 2025" initiative is driving the adoption of large-scale automation, reducing dependency on manual labor, and enhancing supply chain efficiency [20]. The Automotive Industry Market Industry is expected to undergo growth from 2132.16 (USD billion) in 2024 to 2999.03 (USD billion) by 2035. The Automotive Industry Market CAGR (growth rate) is forecast to be approximately 3.15% during the 2025–2035 period [21].

The automobile sector is confronted with increasing supply chain risks, notably highlighted by shortages in semiconductors, which pushed back more than 3 million units of automobile production worldwide in 2022, highlighting the vulnerability of a highly dependent system on just-in-time procurement and intricate constituent networks [22,23]. It is estimated that revenues lost as a result of such disruptions amount to USD 210 billion on an annual basis [24]. In addition, the average lead time for critical auto-related semiconductors has now exceeded 24 weeks, thereby causing systemic production inefficiencies [23]. At the same time, security threats are piling up: losses to ransomware in the automotive sector rose from USD 74.7 million to USD 209.6 million in the first half of 2023 alone, as the number and value of attacks against connected systems are on the rise [22,25,26]. Piling atop the pressure, the sector is also confronting speeding-up labor and skills challenges, with 78% of automotive makers increasing investment in upskilling since 2020, yet still estimating a USD 237 billion worldwide skills shortfall in 2030 [25]. Alongside these performance challenges, overall marketplace trends indicate levelling-off growth and profitability for automotive suppliers, whose EBIT margins remain approximately in the range of 4.7–5.3%, way off pre-COVID levels and lagging behind other sectors [26]. Combined, these threats—long-term supply chain exposure, cyber risks, talent gaps, and margin squeeze—make the necessity of Industry 5.0 integration particularly urgent for the auto industry.

With the move towards Industry 5.0, first-time users of collaborative robots in automotive assembly lines have reported measurable gains in task satisfaction and safety measures. Operators indicate they have decreased physical burden and improved ergonomics when using cobots [27,28]. Simultaneously, adaptive human-machine interfaces—including AI-powered copilots—improved well-being and cognitive load because they automatically adjusted the complexity of interactions according to users' abilities [29,30]. Involving workers in the co-design of cyber-physical systems for socially sustainable innovation has been acknowledged as critical [31]; this type of user involvement has been found to enhance usability and trust while decreasing barriers to adoption. These endeavors have been found to decrease physical and cognitive risks, enhance resilience for human-robot symbiosis, and emphasize the importance of inclusion and equity for workforce development to ensure the equitable distribution of benefits in the automotive sector [32]. In this regard, human-centered, participatory, and inclusive design becomes central for effective risk management and an ethical approach for deployment in Industry 5.0.

The aim of this study is to identify, evaluate, and prioritize key Industry 5.0 enablers for sustainable automotive manufacturing by using a systematic Delphi method based on expert feedback from industrial, technological, and sustainability domains. This work

intends to provide a consensus model that guides auto makers and policymakers in the effective implementation of human-oriented, resilient, and environmentally sustainable practices in the Industry 5.0 age.

The research questions are: What are the most critical enablers of sustainable automotive manufacturing under Industry 5.0? How can they be prioritized based on expert consensus to inform future implementation strategies?

In order to achieve its aim, this research establishes the following objectives:

1. To bring together the key elements of Industry 5.0 (human-centricity, sustainability, and resilience) as they apply to automotive manufacturing.
2. To develop a comprehensive set of Delphi statements on the potential technological, organizational, and policy enablers of sustainable automotive manufacturing in the context of Industry 5.0.
3. To invite a panel of experts to take part in a structured Delphi process to indicate and prioritize key Industry 5.0 enablers for sustainable automotive manufacturing.
4. To identify and rank top enablers of Industry 5.0 by expert consensus with particular attention to:
  - Human-machine collaboration and workers' well-being;
  - Green production and circular economy integration;
  - Resilience and digital transparency;
  - Performance and sustainability KPIs for decision-making.

Researchers have applied Delphi and fuzzy multi-criteria decision-making methods, such as Fuzzy AHP, TOPSIS, VIKOR, DEMATEL, and DEA, to evaluate suppliers in cases of uncertainty in the automotive industry. In [33], Fuzzy Delphi and AHP-DEMATEL were applied to select suppliers in capital procurement of the Indian automotive sector. In [34], the researchers applied a Fuzzy AHP approach to supplier selection for a leading Indian car maker. Fuzzy AHP was combined with Fuzzy TOPSIS and Fuzzy WASPAS to rank the suppliers within the Moroccan auto-motive setting [35]. Another study [36] integrated Fuzzy TOPSIS, Fuzzy AHP, and Fuzzy VIKOR in order to select India's bus-body suppliers. Fuzzy ranking was proposed in [37], applying Fuzzy AHP and Fuzzy DEA in an auto-lighting systems company in Taiwan. Fuzzy AHP was combined with Z-TOPSIS in an automobile manufacturing company in [38]. While these methods adequately provide for uncertainty and ranking, none simultaneously combines fuzzy ranking, consensus trajectory mapping (for visualizing evolving expert consensus across Delphi rounds), and their synthesis. The present study's method bridges this specific methodological void by synoptically employing these components in a Delphi-MCDA system applicable to the automotive sector.

This research utilizes a Delphi method, a consensus trajectory mapping and fuzzy ranking techniques to identify and rank expert opinions on identifying, evaluating, and prioritizing the key Industry 5.0 enablers for sustainable automotive manufacturing. The Delphi method is a structured communication process that uses several rounds of surveys, to come to an expert consensus [39]. Fuzzy logic-based techniques are employed for determining the degree of agreement and to cover the uncertainty and vagueness rather than uncertainty in human judgments. Moreover, to ensure the robustness of the results, a sensitivity analysis is carried out.

Despite the expansion of the extant literature concerning Industry 5.0, the prevailing research typically identifies generalized trends rather than conducting sector-specific studies within the automotive context. A review of the extant literature on the subject reveals an absence of comprehensive research. According to the knowledge of the authors, the combination of consensus methods (e.g., Delphi) with fuzzy ranking and consensus trajectory mapping has not yet been fully explored in this area, which represents a strength

of this research paper. This research focuses on identifying enablers in the automotive setting. Automobile organizations face uncertainty about where to prioritize innovations, particularly in the areas of sustainability, personalization, and smart automation. This study is based on fuzzy ranking and consensus trajectory mapping to support evidence-based decision making, allowing organizations to engage in the prioritization of investment on major innovations based on the evaluation of experts.

## 2. Materials and Methods

### 2.1. The Delphi Study

A three-round Delphi study was employed to identify, evaluate, and prioritize key enablers of Industry 5.0 for sustainable automotive manufacturing, utilizing a structured Delphi approach with expert judgment infusing industrial, technological, and sustainability fields. This study was conducted from January to June 2025. The methodology was employed to provide guidance in the implementation process and in the analysis of the resulting data [39]. Three consecutive rounds were realized. In the initial round, the participants were permitted to utilize their expertise on the enablers of Industry 5.0 for the purpose of this study. The second round aimed to bring together divergent opinions, and the third round-built consensus. A Delphi study panel constitutes experts who have been purposively selected for their knowledge in the field of the study's research focus [40]. This research focused on the utilization of fuzzy ranking between Delphi iterations, which facilitates the formulation of decisions that are more informed, precise, and consensus aware. It ensures that the most salient statement does not simply equate to the largest following; instead, it is the one with the highest conviction among professionals. The analysis was thus rendered a more effective tool for guiding implementation strategies in uncertain, high-risk areas, such as sustainable production in Industry 5.0 [41].

While this study employed a Delphi technique involving a structured process in obtaining expert opinions, it should be pointed out that the original aim was to reach a consensus on Industry 5.0 factor prioritization and the importance level of pre-determined factors and not iteratively refine the questionnaire items themselves [39,42,43].

### 2.2. Participants

Romania is a Central and Eastern European country and has been a member of the European Union since 2007. Romania has a diverse industrial structure with clearly defined industrial sectors and a well-established automotive industry, as well as electronic and IT services. The country has developed as an emerging source of advanced manufacturing and digital innovation, due to a solid base of engineering training and sizeable investments in Industry 4.0 and Industry 5.0 technologies. As part of the European Union, Romania shares a common industrial policy with European Union member states in promoting sustainable practices, digital transformation, and social/inclusive innovation-orientated industrial policy.

In this study, 48 experts from Romania who met the inclusion criteria were contacted using the snowball sampling method. The experts in question hailed from both the private and public sectors. Of the 48 experts identified as potential participants, 20 were willing and able to take part in each round. The Delphi panel consisted of 20 experts, who were selected based on their mature experience and knowledge in the fields of automotive manufacturing and green technologies. The participants included senior research and development (R&D) managers, automotive company sustainability managers, academic researchers specialized in industrial innovation and sustainability, policy-makers interested in industry regulation, and technology providers of AI and robotic solutions. The participants worked in Romania as well as in various countries from Europe. The panelists were drawn from diverse

geographic regions within Romania. There were requirements for selection based on at least five years of experience relevant to the subject and evidence of experience through research outputs or management. The evaluation was conducted anonymously in three phases to facilitate objective and constructive comments, with iterative summaries being presented to hone collective opinion and reach a consensus on the most significant Industry 5.0 declarations to underpin sustainability in car production. The interview participants included fourteen males and six females; for details regarding the experts, see Table 1.

**Table 1.** Demographic characteristics of the Delphi study respondents.

Type	Work Position	Respondent	Work Experience (Years)
University	University 1	Professor PhD	21
	University 2	Associate Professor PhD	15
	University 3	Professor PhD	24
	University 4	Professor PhD	25
Companies focused on AI and robotics	Company 1	Digital Transformation Manager	8
	Company 2	Senior Engineer for Digital Twin Technologies	10
	Company 2	General Manager	19
	Company 3	General Manager	24
	Company 3	AI Solutions Architect	9
	Company 4	Senior Software Engineer (AI/Robotics)	6
Department of Economic and Social Policies	Representative 1	Advisor on Industrial Policy and Sustainability	8
	Representative 2	Director	13
Factory	Factory 1	Production Manager	9
	Factory 2	R&D Engineer—Additive Manufacturing and Automation General Manager	12
	Factory 3	Green Manufacturing Specialist	7
	Factory 3	Production Manager	10
	Factory 4	Industry Program Leader	8
	Factory 5	Technical Consultant	14
	Factory 5	General Manager	9
	Factory 5	Production Manager	10

The questionnaire focused on identifying and prioritizing the key enablers of Industry 5.0 for building sustainable automotive manufacturing. The items were conceived after a complex study of the literature and the specialized practitioners' publications [10–12,44–59].

The questionnaire contained items regarding workforce empowerment; environmental sustainability and green manufacturing; digitalization, automation, and resilience; economic sustainability and performance metrics; and cross-domain and system-level considerations. The confidentiality of the responses was ensured. In order to mitigate the risk of issues or misinterpretation of statements prior to each round, a trial run was conducted.

### 2.3. Rounds Process

The Delphi study commenced with the first round, wherein the selected panel of experts independently appraised a series of meticulously crafted statements pertaining to identify, evaluate, and prioritize key enablers of Industry 5.0 for sustainable automotive manufacturing. Each expert provided anonymous ratings, on a Likert scale, ranging from 1 to 5, from least to most important, allowing for a wide range of initial opinions without group influence or peer pressure (see Table 2). After collecting the results, the responses were analyzed statistically to determine measures of central tendency and measures of dispersion (the mean, standard deviation, interquartile range, etc.).

**Table 2.** Range of scores and level of importance.

Range	Level
1.00–1.80	unimportant
1.81–2.60	of little importance
2.61–3.40	moderately important
3.41–4.20	important
4.21–5.00	very important

In the second round, controlled, anonymized feedback was shared with the panel of experts, and the group means were summarized along with any divergence and convergence. The data were then reviewed by experts, who were tasked with reconsidering and updating their initial rates based on the responses from the group. This iterative reflection helped the panel to coalesce their thoughts and contribute to reducing disparate ratings.

The third round of feedback and re-assessment was aimed at eliciting expert consensus further. By this time, the majority of participants had adjusted their rates based on their peers, resulting in a greater degree of overlap and agreement, as well as a more consistent set of rates. Throughout all three rounds, the use of anonymity and the independence of thought processes were a critical element to allow for the aggregation of expert opinions over multiple periods. The final round's results represent a more refined consensus of the group of experts and represent a statistically reliable consensus that can contribute to informing subsequent decision-making and research.

#### 2.4. The Survey

The data were collected in an individual and anonymous manner to ensure authoritative responses from the experts. Descriptive statistics were performed. The mean scores of all the executives' ratings were presented to the twenty participants in the second round and third round. They were then asked to review each activity and rate each item again on a scale of 1 to 5 based on their level of importance. At the end of the third round of data collection, a consensus was reached. The survey contained five categories and a total of 25 items (see Table A1).

### 3. Results

#### 3.1. Statistical Analysis

After identifying the items for this study, a comprehensive analysis was performed. The following variables were computed as  $\mu$  (mean): average expert rating (usually a scale in the range of 1–5);  $\sigma$  (standard deviation): measures variability in ratings (lower = greater consensus), IQR (interquartile range): spread of the middle 50% of ratings (lower = tighter agreement), and rWG (inter-rater agreement): reliability coefficient values closer to 1 indicate a stronger agreement. See Table 3 for a summary of these statistical descriptors.

**Table 3.** Statistical descriptors for each round.

Item Number	Item	Round 1 ( $\mu$ , $\sigma$ , IQR, rWG)	Round 2 ( $\mu$ , $\sigma$ , IQR, rWG)	Round 3 ( $\mu$ , $\sigma$ , IQR, rWG)
1	The implementation of collaborative robots (cobots) in assembly lines enhances occupational safety and improves employee satisfaction.	4.10, 1.18, 1.19, 0.69	4.15, 1.13, 1.18, 0.78	4.33, 0.92, 1.17, 0.87
2	The productivity and overall health of employees are elevated with the use of adaptive human-machine interfaces, such as AI copilots.	4.47, 0.88, 0.97, 0.63	4.56, 0.73, 0.84, 0.66	4.74, 0.69, 0.76, 0.69

Table 3. Cont.

Item Number	Item	Round 1 ( $\mu$ , $\sigma$ , IQR, rWG)	Round 2 ( $\mu$ , $\sigma$ , IQR, rWG)	Round 3 ( $\mu$ , $\sigma$ , IQR, rWG)
3	The foundation of sustainable integration of the workforce is personalized and lifelong learning in both digital and physical systems.	4.16, 1.11, 0.98, 0.68	4.34, 1.10, 0.80, 0.69	4.36, 0.82, 0.51, 0.78
4	Automotive factories in Industry 5.0 should prioritize inclusivity and equity in workforce development.	4.04, 0.84, 1.17, 0.67	4.21, 0.62, 0.89, 0.75	4.32, 0.56, 0.75, 0.85
5	The employee co-design of cyber–physical systems is the prime mover of socially sustainable innovations.	4.43, 1.01, 1.12, 0.68	4.55, 0.84, 0.97, 0.72	4.76, 0.59, 0.61, 0.88
6	Closed-loop recycling systems for automotive components (batteries, aluminum) are essential for the circular economy’s objectives.	4.35, 0.89, 1.14, 0.71	4.41, 0.72, 0.96, 0.77	4.52, 0.61, 0.70, 0.81
7	Local renewable energy sources (rooftop solar, hydrogen) must enable green automotive manufacturing.	4.18, 0.94, 1.19, 0.65	4.30, 0.79, 0.94, 0.70	4.42, 0.69, 0.79, 0.79
8	Additive manufacturing (3D printing) has great possibilities to cut down material waste and carbon footprints from automotive component manufacturing.	4.21, 1.02, 1.18, 0.68	4.34, 0.88, 0.95, 0.74	4.47, 0.66, 0.66, 0.83
9	Life cycle (LC) analysis must be considered in product design from the research and development stage.	4.43, 0.92, 1.15, 0.70	4.54, 0.81, 0.88, 0.76	4.62, 0.69, 0.71, 0.80
10	Sustainable supplier assessment should incorporate life cycle carbon footprint, material toxicity, and recyclability metrics.	4.19, 0.94, 1.14, 0.69	4.33, 0.83, 0.92, 0.72	4.45, 0.74, 0.74, 0.79
11	Digital twins of factories and supply chains will assist in maximizing sustainability and enable proactive strategic decisions.	4.32, 1.06, 1.20, 0.66	4.48, 0.90, 0.96, 0.72	4.59, 0.77, 0.70, 0.83
12	Autonomous intralogistics (AMRs) have exhibited a higher level of operational resilience and decreased energy utilization.	4.28, 0.97, 1.17, 0.68	4.40, 0.82, 0.92, 0.74	4.51, 0.67, 0.65, 0.80
13	Industry 5.0 must place a strong focus on system redundancy and modularity to be resilient against future supply chain disruptions.	4.15, 1.12, 1.21, 0.64	4.27, 0.95, 0.98, 0.70	4.35, 0.75, 0.74, 0.76
14	AI—predictive maintenance reduces waste and extends the lifespan of equipment employed in automotive production.	4.30, 0.91, 1.13, 0.70	4.44, 0.80, 0.90, 0.74	4.55, 0.72, 0.69, 0.79
15	Blockchain provides traceability in supply chains necessary for ethics and compliance to sourcing.	4.11, 0.95, 1.19, 0.63	4.24, 0.82, 0.91, 0.70	4.36, 0.69, 0.72, 0.78
16	Sustainable operations (e.g., energy efficient equipment and waste valorization) will improve cost performance in the long term.	4.22, 1.00, 1.18, 0.67	4.38, 0.89, 0.93, 0.73	4.49, 0.71, 0.70, 0.80
17	Triple Bottom Line (TBL) sustainability metrics must be included in all Key Performance Indicators (KPIs).	4.35, 0.88, 1.10, 0.69	4.46, 0.78, 0.88, 0.75	4.58, 0.68, 0.65, 0.82
18	Investments in sustainability and digital resilience will lead to higher brand equity and customer loyalty.	4.29, 0.95, 1.15, 0.67	4.37, 0.84, 0.92, 0.71	4.48, 0.72, 0.71, 0.79
19	Industry 5.0 implementation must be economically viable for auto-supply chain Small and Medium-size Enterprises (SMEs).	4.07, 1.01, 1.22, 0.62	4.18, 0.85, 1.00, 0.68	4.30, 0.74, 0.78, 0.75
20	Green public procurement and sustainability incentives are necessary to upscale sustainability across the sector.	4.24, 0.98, 1.17, 0.66	4.39, 0.84, 0.93, 0.72	4.49, 0.69, 0.70, 0.79
21	Integration of AI with real-time energy monitoring software can optimize plant-wide energy efficiency.	4.19, 1.03, 1.21, 0.65	4.31, 0.86, 0.97, 0.70	4.42, 0.75, 0.74, 0.78
22	Sustainability by design needs to guide all digitalization initiatives (AI, IoT, robotics) in auto-production.	4.25, 0.95, 1.15, 0.67	4.41, 0.80, 0.88, 0.74	4.53, 0.70, 0.67, 0.81

Table 3. Cont.

Item Number	Item	Round 1 ( $\mu$ , $\sigma$ , IQR, rWG)	Round 2 ( $\mu$ , $\sigma$ , IQR, rWG)	Round 3 ( $\mu$ , $\sigma$ , IQR, rWG)
23	Human-centric design and ethical AI governance are the prerequisites for Industry 5.0's responsible implementation.	4.32, 0.91, 1.12, 0.68	4.45, 0.78, 0.90, 0.75	4.56, 0.65, 0.60, 0.83
24	Resilience and sustainability must be integrated not only in manufacturing, but also in the upstream research and development and design chains.	4.17, 0.99, 1.19, 0.66	4.28, 0.83, 0.93, 0.70	4.41, 0.71, 0.71, 0.79
25	Tomorrow's automotive plants must have interdisciplinary cooperation (engineers, data scientists, ethicists, and policy-makers).	4.12, 1.02, 1.20, 0.63	4.25, 0.88, 0.95, 0.69	4.38, 0.72, 0.67, 0.77

### 3.2. Interpretation of the Statistical Results

The Delphi study applied 25 statements across three rounds to quantify expert agreement across various statistical measures: mean ( $\mu$ ), standard deviation ( $\sigma$ ), interquartile range (IQR), and inter-rater reliability (rWG). The examination of these measures across rounds provides and insight into changing expert agreements and the results' reliability.

Regarding the consensus level and central tendency (mean— $\mu$ ), the mean values for all statements were consistently high across all rounds, usually above 4.0 on a 5-point scale, showing a high overall agreement from the expert panel. For example, “The productivity and overall health of employees is elevated with the use of adaptive human-machine interfaces, such as AI copilots” statement averaged 4.47 during Round 1 but went up to 4.74 during Round 3. This shows the growing recognition of the importance of adaptive interfaces as experts re-evaluated the statement with a peer review. “The employee co-design of cyber-physical systems is the prime mover of socially sustainable innovations” statement showed an increase in the mean value from 4.43 to 4.76, reflecting the enhanced consensus that employees' contribution is vital for innovation sustainability. The stable or increasing means across rounds imply panelists either re-confirmed their initial opinions or increased their scores as a result of increased confidence following repeated feedback.

Focusing on reducing variability (standard deviation— $\sigma$ , and interquartile range—IQR), the standard deviation and IQR measure the spread and homogeneity of the expert's marks. For instance, “The implementation of collaborative robots (cobots) in assembly lines enhances occupational safety and improves employee satisfaction” showed a drop in the standard deviation from 1.18 in Round 1 to 0.92 in Round 3, and the IQR was nearly flat (1.19 to 1.17). The decrease in  $\sigma$  indicates that while initial opinions were more spread out and separated, between-rounds experts' scores became closer, demonstrating a higher agreement. In the case of the statement “The foundation of sustainable integration of the workforce is personalized and lifelong learning in both digital and physical systems”, the IQR drastically fell from 0.98 in Round 1 to 0.51 in Round 3, so that the middle 50% of the expert ratings were much closer together, indicating a higher consensus and less variability. This reduction in variability measures means that the Delphi process successfully influenced the panel to converge their views and smooth out differences, resulting in a more consistent group judgment.

Regarding the inter-rater agreement (rWG), the coefficient quantifies the in-group agreement beyond chance. As an example, “The employee co-design of cyber-physical systems is the prime mover of socially sustainable innovations”, a key human-centricity statement, had an improved rWG from 0.68 in Round 1 to a peak of 0.88 in Round 3, showing good reliability and agreement among the experts on this statement by the end of this study. Item “Human-centric design and ethical AI governance are prerequisites for Industry 5.0 responsible implementation” rose from 0.68 to 0.83 rWG, indicating an increasing consensus on the Industry 5.0 digitalization ethical imperatives.

Rounds where values greater than 0.7 were achieved are regarded as strong indicators of agreement, and the majority of statements had achieved or moved past this mark by Round 3.

Regarding the thematic insights from the category of Human-Centricity (items 1–5), high means (higher than 4.3 overall) and improved rWG (over 0.8 in Round 3) present the strong confidence of panelists in employee empowerment technologies, like cobots, adaptive interfaces, and employee co-design. For example, the statement “Human-centric design and ethical AI governance are the prerequisites for Industry 5.0 responsible implementation” had the highest Round 3 mean (4.76) and one of the highest rWG values (0.88), indicating an overwhelming consensus on the advantages of co-design.

For Environmental Sustainability (items 6–10), the statements “Closed-loop recycling systems for automotive components (batteries, aluminum) are essential for circular economy’s objectives” and “Life cycle (LC) analysis must be considered in product design from the research and development stage” received mean ratings of over 4.5 and rWG scores over 0.8, reflecting the strong panel consensus on environmental Industry 5.0 priorities.

In the Digitalization and Resilience category (items 11–15), the statement “Digital twins of factories and supply chains will assist in maximizing sustainability and enable proactive strategic decisions” increased in mean from 4.32 to 4.59 and improved its rWG from 0.66 to 0.83, indicating a higher confidence in the potential of digital instruments for future-oriented decision-making.

From the Economic Sustainability perspective (items 16–20), the statements revealed a relatively lower initial agreement, but subsequently improved consistently. As an example, the statement “Industry 5.0 implementation must be economically viable for auto supply chain Small and Medium Enterprises (SMEs)” increased from a mean of 4.07 to 4.30, with the rWG increasing from 0.62 to 0.75, indicating the rising awareness of SME issues among specialists.

System-Level Factors (items 21–25) indicate statements that emphasize interdisciplinarity and ethical leadership. They saw mean values increase in a consistent pattern and the rWG surpass 0.75, underlining the importance of holistic strategies towards achieving Industry 5.0 success.

### 3.3. Consensus Trajectory Mapping

This research continues with consensus trajectory mapping, which aims to highlight the dynamic process of consensus formation and to recommend items that are of strategic importance or potential. It is imperative to identify items that exhibited strong consensus-building trajectories over time, as opposed to merely focusing on items that received the highest scores.

Figure 1 illustrates the consensus trajectory mapping showing how expert agreement ( $\sigma$ ) and importance ( $\mu$ ) levels for each item changed across each Delphi rounds, and most items progressed towards higher levels of agreement and comparatively higher levels of perceived value.

The consensus trajectory mapping figure summarizes the consensus and perceived importance for each statement across the three Delphi rounds. The horizontal axis denotes standard deviation ( $\sigma$ ), a relative proxy for consensus, where smaller  $\sigma$  values signal a stronger consensus among the experts, while the vertical axis denotes the mean rating ( $\mu$ ), a measure of the importance or relevance of each item. For ease of interpretation, the  $\sigma$ -axis is inverted, so the movement to the right indicates improving consensus, while the movement upwards indicates increasing importance. Each trajectory illustrates a single item plotted from Rounds 1 to 3.

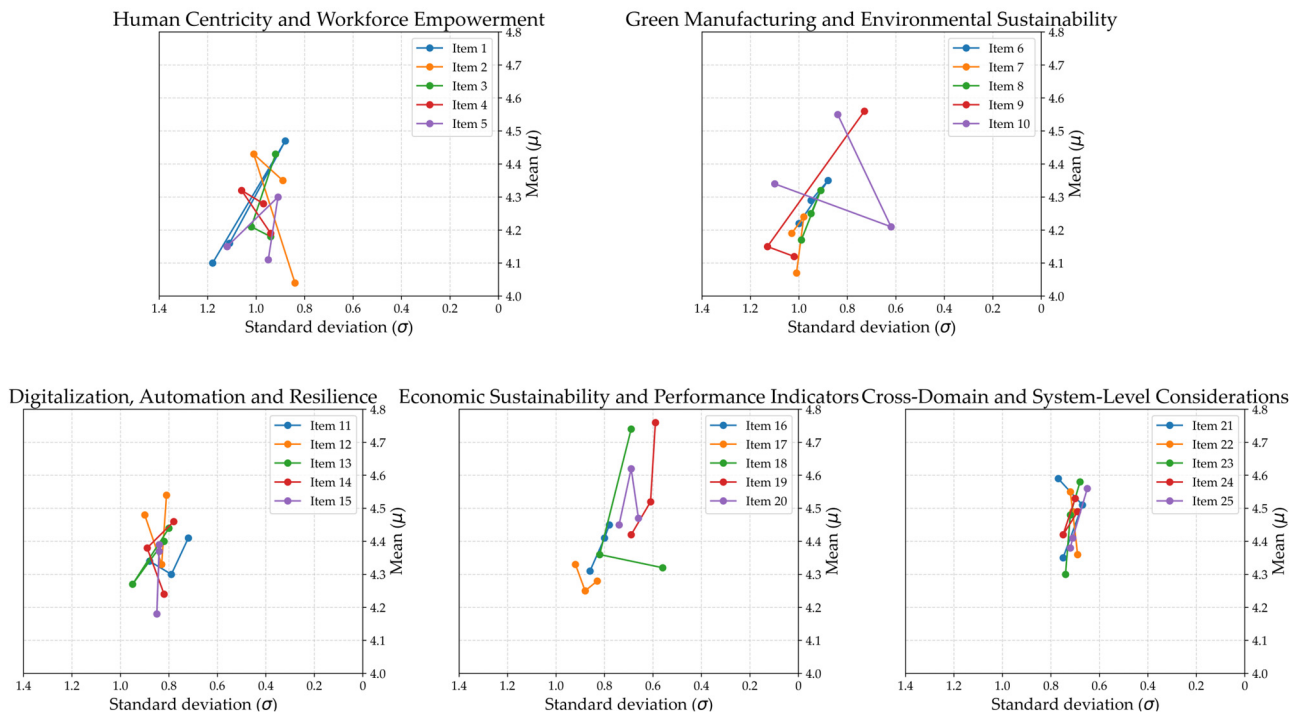


Figure 1. Consensus trajectory mapping.

The mapping for the first category shows a general upwards trajectory in agreement and perceived importance. For the five items, all except one score better in mean scores from Round 1 to Round 2 and then plateau or decrease minimally in Round 3. The suggestion is that panelists initially converged on judgments towards greater consensus before presenting a slight dispersion in the third round. For example, item 1 ranges from  $\mu = 4.10$  to 4.47 in Round 2, then 4.16 in Round 3, and its  $\sigma$  is also unstable. On the whole, the pattern shows the initial convergence and subsequent relativity of secondary significance or comprehension, such as tends to happen in problems where human centrality is multidirectional and culturally nuanced. The standard deviations tend to decrease or remain moderate, namely, there is a good degree of agreement, although with some final-round deviation.

The second category has one of the more active consensus trajectory mappings, with considerable agreement and item value improvements, especially in Rounds 2 and 3. All items reveal increasing mean scores (e.g., item 9 from 4.12 to 4.56), and the standard deviations decrease substantially by Round 3 (e.g., item 9 from 1.13 to 0.73). This suggests that the experts coalesced over shared priorities of environmental sustainability in the long term. The intense consensus gains indicate an increasing understanding or convergence of opinion, potentially due to external normative pressures (e.g., Environmental, Social, and Governance performance or European Union Green Deal conformity). The convergence indicates high shared relevance, perhaps resulting from the tangible operational or regulatory experience of participants.

The plot for the third category shows peak and stable mean values for all items (e.g., item 12 remains above  $\mu = 4.3$  in all waves), with relatively low and stable standard deviations (commonly  $\sigma < 0.9$ ). The lowest variability indicates the earliest possible consensus and stable consensus, showing the category's self-designated start-point status in Industry 5.0 changes. The slight gain in mean for a few items in Round 3 (e.g., item 14's mean goes from 4.24 to 4.38, then reaches 4.46) shows the panel having an increased awareness of the emerging importance of resilient digital infrastructures as the discussions evolved. It

symbolizes a deepening belief system that digitalization and resiliency are interrelated long-term enablers rather than just passing technological trends.

The fourth category observes the most subtle trend. Mean scores stay high (generally greater than 4.2), with some items having declining means across rounds (e.g., item 18: 4.74–4.36–4.32), perhaps suggesting the use or implementation feasibility of some of those items being reconsidered. The steep fall in their standard deviations (e.g.,  $\sigma$  for item 18 reaches 0.56) could mean that, while experts downgraded the importance, they tended to agree even more on that revised evaluation. This twofold trend—decreasing importance with increased consensus—may be an indicator of economic realism: experts recognize constraints or trade-offs in aggregating performance metrics into broader sustainability portfolios within Industry 5.0.

The items from the last category tend to be converging over rounds, with some mean scores barely changing at all (e.g., item 21: 4.59–4.51–4.35), while standard deviations pull in—largely to  $\sigma$  around 0.7. The trend suggests that while there might have been a tempering of the assessments over individual cross-domain components, they converged more in terms of interpretive framing. This may be due to an increased understanding of system-level interactions following the initial few rounds of deliberation. Notably, item 24 demonstrates a rebound effect ( $\mu = 4.49$ –4.42–4.53), indicating a growing recognition of systemic integration's suitability by the final round. In general terms, the trajectory for this category encapsulates the spirit and inter-disciplinary nature of systems thinking, where convergence is realized through iterations and is relative to the context.

### 3.4. Fuzzy Logic Ranking

For the final prioritization of statements, Fuzzy logic-based ranking was applied. It considers multiple aggregated indicators (mean, standard deviation, IQR, and rWG) to produce a composite score for each item. Fuzzy ranking is predicated on the purpose of achieving global consensus on matters of importance. Items that demonstrate a consistent high performance across all rounds in these domains are prioritized.

The fuzzy ranking scores for all the statements across all three rounds used the following formula and weights:

$$F = 0.4 \mu - 0.2 \sigma - 0.2 \text{IQR} + 0.2 \text{rWG}. \quad (1)$$

The fuzzy ranking formula is intended to integrate both the central point of the expert's opinion and the extent of agreement, based on established Delphi practices. The weighted mean applies a lot of weight to the mean score ( $\mu$ ) since the classical Delphi practice places most of the weight on the average expert view [42,60]. To compensate for expert disagreement, dispersion statistics ( $\sigma$  and IQR) are given negative weights, thus penalizing inconsistency and adjusting for overall variability and outlier resistance [61]. The measure of interrater agreement (rWG) also adds positively to the score for capturing consensus quality as well as that captured by dispersion statistics [62].

This weighting strategy is designed to balance the strength of expert endorsement against the consistency of their agreement in terms of the fuzzy decision-making theory for balancing centrality and uncertainty [63,64]. To ensure reproducibility and rigor, all indicators were normalized prior to aggregation to minimize potential scale effects. Sensitivity analyses were conducted by adjusting the weights over a  $\pm 10\%$  range to test the robustness of the results, hence ensuring transparency and methodological rigor. The fuzzy model of ranking employed in this study relies both on theoretical and pragmatic considerations, so that what is ranked becomes not merely a function of apparent statement importance, but also of consequent quality of expert agreement.

After the scores' computation for each statement in each round ( $F_{R1}$ ,  $F_{R2}$  and  $F_{R3}$ , respectively) the aggregate fuzzy score across rounds by averaging was computed following the following formula:

$$F_{agg} = (F_{R1} + F_{R2} + F_{R3})/3. \quad (2)$$

The results are presented in Table 4.

**Table 4.** Fuzzy scores.

Rank	Item	Statement	$F_{R1}$	$F_{R2}$	$F_{R3}$	$F_{agg}$
1	2	The productivity and overall health of employees is improved with the use of adaptive human–machine interfaces, such as AI copilots.	1.544	1.642	1.744	<b>1.6433</b>
2	5	The employee co-design of cyber–physical systems is the prime mover of socially sustainable innovations.	1.482	1.602	1.840	<b>1.6413</b>
3	9	Life cycle (LC) analysis must be considered in product design from the research and development stage.	1.498	1.630	1.728	<b>1.6187</b>
4	17	Triple Bottom Line (TBL) sustainability metrics must be included in all Key Performance Indicators (KPIs).	1.482	1.602	1.730	<b>1.6047</b>
5	23	Human-centric design and ethical AI governance are the prerequisites for Industry 5.0's responsible implementation.	1.458	1.594	1.740	<b>1.5973</b>
6	6	Closed-loop recycling systems for automotive components (batteries, aluminum) are essential for the circular economy's objectives.	1.476	1.582	1.708	<b>1.5887</b>
7	14	AI—predictive maintenance reduces waste and extends the lifespan of equipment employed in automotive production.	1.452	1.584	1.696	<b>1.5773</b>
8	22	Sustainability by design needs to guide all digitalization initiatives (AI, IoT, robotics) in auto-production.	1.414	1.576	1.700	<b>1.5633</b>
9	11	Digital twins of factories and supply chains will assist in maximizing sustainability and enable proactive strategic decisions.	1.408	1.564	1.708	<b>1.5600</b>
10	12	Autonomous intralogistics (AMRs) have exhibited a higher level of operational resilience and decreased energy utilization.	1.420	1.560	1.700	<b>1.5600</b>
11	18	Investments in sustainability and digital resilience will lead to higher brand equity and customer loyalty.	1.430	1.538	1.664	<b>1.5440</b>
12	20	Green public procurement and sustainability incentives are necessary to upscale sustainability across the sector.	1.398	1.546	1.676	<b>1.5400</b>
13	16	Sustainable operations (e.g., energy efficient equipment and waste valorization) will improve cost performance in the long term.	1.386	1.534	1.674	<b>1.5313</b>
14	8	Additive manufacturing (3D printing) has great possibilities to cut down material waste and carbon footprints from automotive component manufacturing.	1.380	1.518	1.690	<b>1.5293</b>
15	10	Sustainable supplier assessment should incorporate life cycle carbon footprint, material toxicity, and recyclability metrics.	1.398	1.526	1.642	<b>1.5220</b>
16	7	Local renewable energy sources (rooftop solar, hydrogen) must enable green automotive manufacturing.	1.376	1.514	1.630	<b>1.5067</b>
17	4	Automotive factories in Industry 5.0 should prioritize inclusivity and equity in workforce development.	1.348	1.532	1.636	<b>1.5053</b>
18	3	The foundation of the sustainable integration of the workforce is personalized and lifelong learning in both digital and physical systems.	1.382	1.494	1.634	<b>1.5033</b>
19	24	Resilience and sustainability must be integrated not only in manufacturing, but also in upstream research and development and design chains.	1.364	1.500	1.638	<b>1.5007</b>
20	21	Integration of AI with real-time energy monitoring software can optimize plant-wide energy efficiency.	1.358	1.498	1.626	<b>1.4940</b>
21	15	Blockchain provides traceability in supply chains necessary for ethics and compliance to sourcing.	1.342	1.490	1.618	<b>1.4833</b>

Table 4. Cont.

Rank	Item	Statement	F <sub>R1</sub>	F <sub>R2</sub>	F <sub>R3</sub>	F <sub>agg</sub>
22	25	Tomorrow's automotive plants must have interdisciplinary cooperation (engineers, data scientists, ethicists, and policy-makers).	1.330	1.472	1.628	<b>1.4767</b>
23	13	Industry 5.0 must place a strong focus on system redundancy and modularity to be resilient against future supply chain disruptions.	1.322	1.462	1.594	<b>1.4593</b>
24	19	Industry 5.0 implementation must be economically viable for auto-supply chain Small and Medium-size Enterprises (SMEs).	1.306	1.438	1.566	<b>1.4367</b>
25	1	The implementation of collaborative robots (cobots) in assembly lines enhances occupational safety and improves employee satisfaction.	1.304	1.354	1.488	<b>1.3820</b>

For a better overview, Figure 2 illustrates the statements' ranking according to the mean score  $F_{agg}$ , with error bars showing each item's standard deviation across the three rounds.

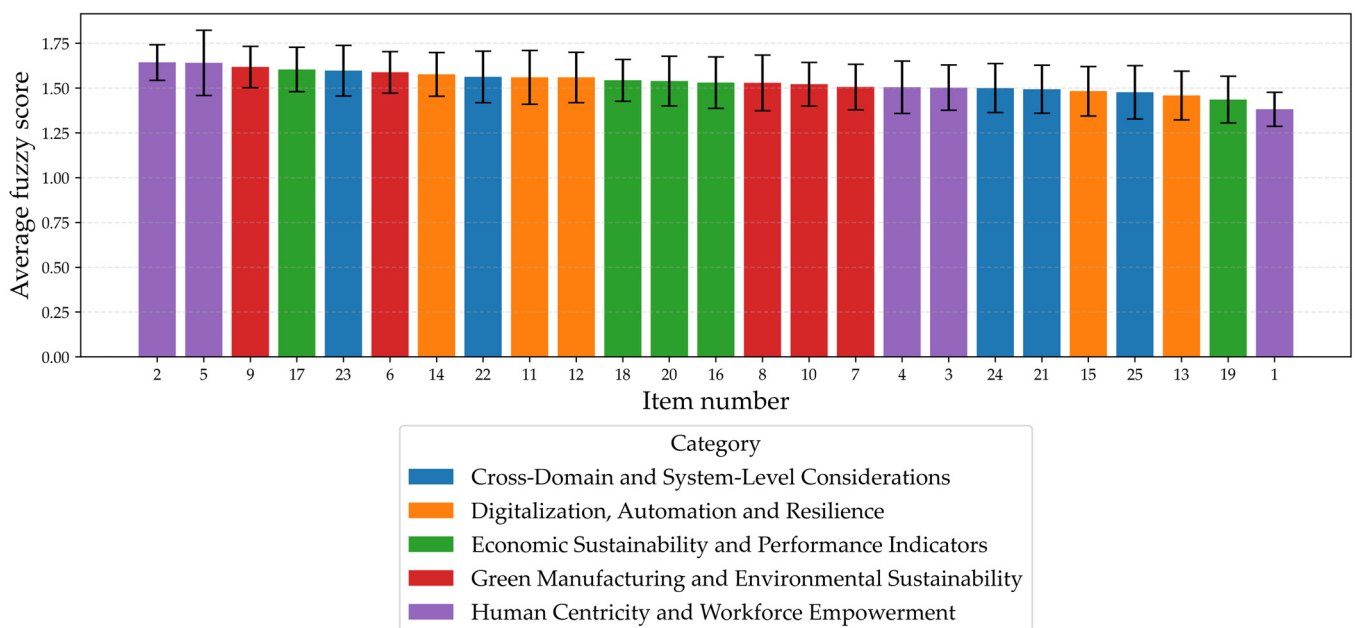


Figure 2. Statement ranking by category.

The fuzzy ranking analysis across three Delphi rounds highlights the relative consistency and priority experts assign to key statements for Industry 5.0 within the automotive manufacturing industry. The approach used of aggregation not only considers the average degree of agreement (mean ratings), but also variability (standard deviation, interquartile range) and inter-rater agreement (rWG), thus providing a richer insight into both the strength and the reliability of experts' opinions.

In the first category, analyzing human-centricity and workforce empowerment, two items, statements 2 and 5, have the highest positions in the ranking. This mirrors a strong expert consensus that workers' input into innovation and human-machine symbiosis are key enablers of Industry 5.0. The highest rated proposition (regarding AI copilots) highlights not just productivity, but also well-being and mental support, thereby inferring that the digital augmentation of human capabilities is of the highest concern. However, statement 1 (on collaborative robots) from this category has the lowest rank of all 25 items, possibly due to its perceived technological maturity or narrow scope. While experts may regard cobots as foundational, they may consider them to be insufficient in isolation. In comparison to more holistic empowerment strategies, such as co-design or adaptive AI, cobots are regarded as a component of a broader framework.

In the second category, the enablers of sustainability demonstrate commendable yet not pre-eminent rankings, with life cycle analysis (LCA) at rank 3, underscoring the expert consensus on the integration of sustainability by design in early R&D. Closed-loop recycling (rank 6) is also high, reflecting the urgency of achieving the circular economy goals in the automotive components sector. The lower rankings for renewable energy (rank 16) and supplier evaluation metrics (rank 15) suggest that these may be regarded as secondary enablers or dependent on external policies (e.g., procurement incentives) to a greater extent than factory internal strategies.

In the third category, the prominence of digital twins, AI predictive maintenance, and autonomous mobile robots (AMRs) in high rankings suggests a prevailing consensus that resilient automation and data-driven operations are imperative. These systems have been demonstrated to provide both operational efficiency and energy/waste reductions, thus rendering them dual-purpose enablers. Blockchain (rank 21) and system redundancy (rank 23) rank low in this category, possibly due to implementation complexity or perceived lack of immediate return on investment.

In the fourth category, comprising economical statements, item 17—integration of sustainability in performance KPIs—ranks fourth overall. This confirms the inseparability of economic sustainability from environmental and social performance in Industry 5.0. However, statement 19 on SME viability ranks 24th, suggesting that experts recognize the challenge, but may lack consensus on how to operationalize this across small firms, which could potentially compromise the implementation of the statement.

The results for the fifth category of items show that experts place significant value on a set of overarching ethical and design principles, with ethical AI governance (rank 5) and sustainability by design (rank 8) emerging as highly ranked integrative strategies. The lower rankings assigned to statement 25 (interdisciplinary collaboration) and energy AI systems may be indicative of these theoretical concepts being perceived as intricate or as yet unproven on a large scale within the sector.

A sensitivity analysis was conducted to evaluate the robustness of the Delphi-based fuzzy rankings under variations in the weighting of importance (mean,  $\mu$ ) and consensus (standard deviation,  $\sigma$ ; interquartile range, IQR; and rWG) indicators [65]. The baseline weights were set at  $\mu = 0.40$ ,  $\sigma = 0.20$ , IQR = 0.20, and rWG = 0.20, and alternative scenarios examined one at a time  $\pm 10\%$  perturbations around the baseline, renormalized to maintain a total weight of one. For each scenario, robustness metrics were computed, including Spearman's rank correlation versus the baseline, top 5 rank overlap, and the maximum rank change.

Overall, the rankings proved to be robust: Spearman's correlations remained high across all scenarios, and the order of the top 5 items remained unchanged across all tested scenarios. A maximum of two items changed rank in some scenarios, indicating that strategic conclusions are not an artifact of specific weight choices. The results are presented in Table 5, where in the first column, the weight change is indicated for each of the tested scenarios (for instance, " $\mu + 10\%$ " indicates a 10% increase in the weight of  $\mu$ , etc.).

**Table 5.** Sensitivity analysis results.

Scenario	Spearman $\rho$	Top 5 Statements Overlap Count	Maximum Rank Change
$\mu + 10\%$	0.999	5	1
$\mu - 10\%$	0.999	5	1
$\sigma + 10\%$	0.998	5	1
$\sigma - 10\%$	0.997	5	2
IQR + 10%	0.997	5	2
IQR - 10%	0.999	5	1
rWG + 10%	1	5	0
rWG - 10%	1	5	1

## 4. Discussion

This Delphi study provides new insights pertaining to the evolving role of the tenets of Industry 5.0 in the automotive industry and presents a shift away from automation-based paradigms towards more human-centric, resilient, and sustainable manufacturing ecosystems. Overall, the experts' evaluations over the rounds of the Delphi process indicated an increasing level of consensus on the expectation of upper management to consider equivalently technological advancement while weighing human and environmental values that characterize Industry 5.0.

The consensus trajectory mapping across consensus categories reveals a well-modeled evolution of expert opinion during iterative rounds of the Delphi process that is bound by cognitive convergence and strategic rethinking. All data point towards an increasing consensus (decreasing standard deviations) that coexists with steady or rising importance scores, thus making a strong case for the gradual clarification and consolidation of views by experts over time. Statements concerning digitalization, automation, and resilience represent an early decision with a high degree of consensus: they are considered fundamental to Industrial 5.0. Conversely, economic sustainability and cross-domain considerations keep their reconsideration dynamic—a testimony to the complexity and trade-offs faced when incorporating wide systemic and economic considerations. By the last round, mature opinions were obtained, characterized not just by a consensus, but well-balanced and informed prioritization. This consequently establishes the robust role played by the Delphi method in creating shared knowledge and foresight for action, especially within the multi-disciplinary surroundings of Industry 5.0 in the automotive field.

The utilization of fuzzy ranking techniques provided a more informative prioritization of thematic areas. The fuzzy approach allowed the authors to retain some nuances of priority, and, in this case, it progressed the interpretation of priorities by highlighting gradients of support, rather than mere agreement or disagreement.

Top enablers to prioritize are adaptive AI–human interfaces, employee co-design, life cycle analysis in early R&D, TBL metrics embedded in KPIs, and ethical AI governance. The proposal from the authors is a combination of digital and human-centric strategies, e.g., employee-designed AI systems; use of early-stage sustainability tools (e.g., LCA) to influence both innovation and compliance; and embed ethical frameworks and KPI alignment in a systemic way to centrally integrate goals across factory and supply chain.

The findings of this research illustrate the need for interdisciplinary research into how the concepts of Industry 5.0 can be operationalized in current automotive production systems. The persistence of these discrepancies in select domains is indicative of challenges that are unique to specific technological domains. However, these challenges are also a manifestation of the prevailing socio-political and ethical issues that are endemic to local contexts. A way to surmount these challenges is through collaborative efforts across various sectors.

Industry 5.0 prioritizes a people-centric transformation, which incorporates technology as a complement rather than a substitute for human workers [54]. A sustainable factory acknowledges human creativity, human inclusion, and human agency, especially in an industry like automotive manufacturing, where skilled labor is connected to high-technology systems. For instance, automotive manufacturing facilities have the potential to establish co-design laboratories in which personnel can engage with AI developers to formulate decision support tools for vehicle assembly lines.

The assessment, monitoring, and management of sustainability are essential. Otherwise, both the environmental ambitions and social goals rely on aspiration. This research's experts concluded it is equally important to embed metrics into the core operations via frameworks, such as TBL and LCA. For example, a Tier 1 automotive supplier could con-

nect supplier agreements to their sustainability dashboards, with the real-time tracking of emissions, waste, and social compliance.

Resource efficiency and circularity, where materials and energy would be reused/recycled/regenerated within local and resilient systems, would be a key part of sustainability in Industry 5.0. An example of a circular initiative by a car production factory is reclaiming electric vehicles' batteries and reusing raw materials through several product lines.

The idea of resilience in Industry 5.0 is to advance towards systems that can react, predict, and self-optimize to maintain ongoing production through events such as supply chain interruptions, energy crises, or production surprises. Building a digital twin would allow a car production factory to introduce plant-wide interruptions and train their AI systems to reoptimize the flow of materials within minutes.

From a practical perspective, it is time for stakeholders in the automotive sector to apply the knowledge derived from this study to operationalize digital transformation strategies that agree with the values of Industry 5.0. Automakers are moving beyond regulatory compliance with former industry showcases and leveraging an increased emphasis on worker inclusion in the design and deployment of smart systems and worker autonomy, focusing on an ecosystem of adaptability and an ecosystem of sustainability. The roadmap articulated in this study, prioritized by high-consensus items, constitutes a concrete entry point for managers, policymakers, and technology developers in bringing Industry 5.0 to life in their daily operations. Overall, this Delphi study presents a first step in defining the taxonomy of Industry 5.0 characteristics for the automotive sector. By using stakeholder/consumer expert judgments and Fuzzy logic, while observing consensus dynamics, this study identified areas of agreement and emergent areas of dialog that will ultimately help lay the groundwork for informed decision-making and purposeful innovation.

The automotive industry is shifting and evolving substantially, driven by the movement towards electrification, intelligence, and connectedness. Key enabling technologies within Industry 5.0—cobots, AI, IoT, and digital twins—are critical for addressing the impediments and maximizing the opportunities presented by these shifts [66,67]. As the industry adapts to focus on electric vehicles (EVs), Industry 5.0's technologies enable the transition to sustainable manufacturing practices. Cobots and AI-based systems create flexible production lines that can satisfactorily produce an array of EV components while wasting less and consuming less energy. Digital twins are being used to create on-demand, real-time simulations that enable manufacturers to optimize their battery manufacturing processes to improve the performance and useful life of EV batteries. The demand for smarter cars translates to an enhanced manufacturing capability [67]. Industry 5.0 promotes a human-machine collaboration in a way that operators can leverage AI and IoT to monitor and control complex production systems. This ability to collaborate makes operators faster in their decision-making processes, strengthens predictive maintenance protocols, and sustains quality control initiatives that ultimately lead to the production of satisfactory, intelligent vehicles for customer consumption. The growth of connected automobiles requires solid and secure manufacturing networks. Industry 5.0's deployment of 5G and edge computing technologies will likely support the smart factories that manage the massive amounts of data produced by connected automobiles. Technologies supporting the quick processing of data and secure communication will ensure that the production of connected automobiles occurs seamlessly [68,69].

From a risk management viewpoint, human-centered technologies related to Industry 5.0, such as cooperative robotics, adaptable natural human interfaces, and inclusive development of the workforce, provides a proactive approach to reducing the operational, ethical, and organizational risks when they are recognized. By including employees in the design of cyber-physical systems and fostering equity for employees, organizations can avoid or mitigate their employees' resistance behavior to the new technology adoption,

lessen the number of human errors, and raise the level of trust to support the use of the system. The continuous learning that is focused on means that the workforce has a better chance of adapting to an organization's evolving business model and reduces the risk of, and degree of, skills mismatch and skill obsolescence in the rapidly changing industrial landscape. Organizations are moving from reactive to predictive risk management and are no longer just maximizing operational efficiencies when deploying technology; they are designing for resilience and social sustainability. By embedding these principles into the design and deployment of Industry 5.0 systems fitting to the organization, organizations can better anticipate business disruptions, compliance, and long-term stakeholder value.

## 5. Conclusions

The Industry 5.0 market is expected to exhibit significant growth, with projections indicating a surge to USD 310.9 billion by 2029. However, beyond the realm of market value, a paradigm shift of a cultural nature has become evident. The contemporary manufacturing paradigm has evolved from a focus on enhancing the efficiency of mechanical processes to a more holistic approach that emphasizes the synergy between human and machine capabilities within a circular economic framework [70,71].

This study documented and explored Industry 5.0's implications for the automotive industry using a structured Delphi approach, which entailed selecting a panel of experts from nationally renowned organizations in industry and academia. The multi-round consensus process for this study consisted of consensus trajectory mapping and fuzzy ranking, which enabled the identification of top priorities, areas of alignment, and a potential for continued uncertainty, as the transition to more human-centric, sustainable, and resilient industrial structure transformation may lead to greater instability. The Delphi method is a systematic approach that facilitates the generation of expert judgment through multiple iterations. Consensus trajectory mapping is a methodology employed to track longitudinal agreement among experts in order to identify which items have stabilized and which items still require further focus. The fuzzy ranking methodology provides a more nuanced evaluation of item prioritization by considering partial agreement and uncertainty. The sensitivity analysis ensures statements' ranking stability. The combination of these methods serves to enhance the robustness, interpretability and applied relevance of Delphi results.

Certainly, expert consensus captured in this study revealed the importance of human-machine collaboration, cognitive automation, and circular production models for the wider adoption of Industry 5.0's in automotive manufacturing, which is important to also mention as a shift away from, and distinction from, purely efficiency and speed automation processes towards holistic systems, which empower people, personalize mobility offerings, and reduce environmental impacts. Additionally, fuzzy ranking captured a multi-faceted view of support for various innovations and noted that while general support existed for some themes, more work could be performed for others, such as ethical AI, digital sovereignty, and system interoperability.

Of significance was the dynamic tracing of consensus evolution across the Delphi rounds. This provided some understanding of how expert views matured over the Delphi rounds, with some items demonstrating convergence and some aspects clearly reflecting ongoing divergence and additional rich areas for further research. The insights provided for target areas offer not only a strategic pathway for practitioners wishing to operate in alignment with Industry 5.0 values, but also provide a direction for future researchers wishing to explore underdeveloped aspects of discipline, such as inclusive designs principles and socio-technical design approaches in smart manufacturing contexts.

There are differences between automotive companies of all sizes regarding how they execute Industry 5.0 principles, largely because of the differences in resources used, techno-

logical infrastructure, and organizational structures [72]. It is obvious that large automotive enterprises have financial and technological resources that allow them to invest in advanced Industry 5.0 technologies, such as cobots, AI-driven analytics, and digital twins. In addition to being able to deploy collaborative and advanced technologies, large firms will dedicate themselves to implementing these technologies in positions and facilities across the world in ways that leverage their vast resources to innovate and reach economies of scale. Larger firms navigating the principles of Industry 5.0 likely have issues with organizational complexity, as well as legacy managerial inertia and uncertainty in implementing change. Small and Medium-size Enterprises (SMEs) from an economic development perspective are limited in capital and technological knowledge. Their interests of adopting advanced Industry 5.0 technologies may be limited. However, SMEs can benefit from Industry 5.0 principles, where focusing on scalable solutions that foster flexibility and human-centric innovation can assist in the adoption of Industry 5.0 principles. The pathway to Industry 5.0 for SMEs may involve modular automation systems, inclusive open innovation collaborations, industry consortia etc. [73,74].

To underpin the analytical rigor of the debate, it is imperative to say how the expert consensus reached using the Delphi method enriches and challenges the existing frameworks of Industry 5.0. The consensus from this study provides an empirical basis for combining human-centered design, sustainability, and resilience as the foundational pillars of Industry 5.0 based on previous conceptual frameworks that concentrate more on technological innovation than social and environmental dimensions. As opposed to traditional automation paradigms focusing exclusively on productivity and cost-effectiveness, human-focused paradigms place greater emphasis on operators' well-being, amplification of cognition, and adaptive cooperation between human beings and cyber-physical systems [14–16]. The views of specialists also call for introducing sustainability and resilience into the core of industrial transformation, in a way that production systems are rendered resilient to shocks and are attuned to circular economy values. This triangulation of views not only serves to highlight the relevance of Industry 5.0 as a broad socio-technical vision, but also highlights evident tensions, like balancing human-centered personalization with efficiency-generating automation, which should be explored in more depth by the subsequent research.

This research contributes to the extensive literature on Industry 5.0 by situating its principles in one of the most innovation-intensive sectors—automotive manufacturing. To build on these insights, future work should seek to validate them empirically through longitudinal studies, pilot projects, and cross-sectoral comparisons, in order to consolidate the theoretical and practical contributions of Industry 5.0 towards the development of next-generation industrial systems.

This research addresses an important strategic, methodological, and conceptual gap in the emergent dialog on Industry 5.0 in the context of the automotive industry. It clarifies the most significant priorities, provides a structure for evaluating consensus, and allows for the development of a more holistic and human-centered orientation for future manufacturing practices.

#### *Research Limitations*

This study has important limitations. The Delphi method draws on expert experience, which is, although informed, subjective [75]. This study focused on pre-defined Industry 5.0 factors. While it is important to aim for a diversity of panels and representation from academia, industry, and public policy across the automotive suppliers' sector, there are limits inherent in the sample selected and the extent to which it can represent diverse ways of thinking across the entire automotive ecosystem. The Delphi panel was made up of Romanian experts and so may limit the generalization of this study's findings in other geographies and cultures. The experts

were from Romania, but some of them also worked in different European countries. The convenience of requiring experts from the same country maximized participation rates and ease of dissemination of expert opinions; however, it also led to possible regional limitations in that regional policy, industry culture, and market conditions may all influence expert attitudes. Accordingly, the generated findings should be interpreted considering this. Future research could extend the Delphi panel by engaging multi-national stakeholders to include multiple operating environments, regulatory environments, and cultural perspectives, and would bolster the generality and robustness of the findings.

The areas of consensus in this study may well be influenced by the expertise of the experts, in that the conclusions of experts are influenced by the state of knowledge and levels of awareness anywhere from the same moment in time. With Industry 5.0 and the various technologies evolving and changing, innovations could affect the opinions of experts, and therefore some of the conclusions would become less relevant sooner than anticipated. At the same time, various interpretations of meanings of concepts such as “human-centered” or “sustainability”, came from the various backgrounds of the experts. Even with a defined, structured consensus, such variations could also have impacted what the participants rated on the statements and how they interpreted the underlying constructs.

Future studies should investigate the co-design process, ethics of automation, and the measurable empirical metrics of human-centered innovation.

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## Appendix A

**Table A1.** The research survey.

Category	Item Number	Statement
I. Human-Centricity and Workforce Empowerment	1	The implementation of collaborative robots (cobots) in assembly lines enhances occupational safety and improves employee satisfaction.
	2	The productivity and overall health of employees is elevated with the use of adaptive human–machine interfaces, such as AI copilots.
	3	The foundation of sustainable integration of the workforce is personalized and lifelong learning in both digital and physical systems.
	4	Automotive factories in Industry 5.0 should prioritize inclusivity and equity in workforce development.
	5	The employee co-design of cyber–physical systems is the prime mover of socially sustainable innovations.

Table A1. Cont.

Category	Item Number	Statement
II. Green Manufacturing and Environmental Sustainability	6	Closed-loop recycling systems for automotive components (batteries, aluminum) are essential for the circular economy's objectives.
	7	Local renewable energy sources (rooftop solar, hydrogen) must enable green automotive manufacturing.
	8	Additive manufacturing (3D printing) has great possibilities to cut down material waste and carbon footprint in automotive component manufacturing.
	9	Life cycle (LC) analysis must be considered in product design from the research and development stage.
	10	Sustainable supplier assessment should incorporate life cycle carbon footprint, material toxicity, and recyclability metrics.
III. Digitalization, Automation and Resilience	11	Digital twins of factories and supply chains will assist in maximizing sustainability and enable proactive strategic decisions.
	12	Autonomous intralogistics (AMRs) exhibited a higher level of operational resilience and decreased energy utilization.
	13	Industry 5.0 must place a strong focus on system redundancy and modularity to be resilient against future supply chain disruptions.
	14	AI—predictive maintenance reduces waste and extends the lifespan of equipment employed for automotive production.
	15	Blockchain provides traceability in supply chains necessary for ethics and compliance to sourcing.
IV. Economic Sustainability and Performance Indicators	16	Sustainable operations (e.g., energy efficient equipment and waste valorization) will improve cost performance in the long term.
	17	Triple Bottom Line (TBL) sustainability metrics must be included in all Key Performance Indicators (KPIs).
	18	Investments in sustainability and digital resilience will lead to higher brand equity and customer loyalty.
	19	Industry 5.0 implementation must be economically viable for auto-supply chain Small and Medium-size Enterprises (SMEs).
	20	Green public procurement and sustainability incentives are necessary to upscale sustainability across the sector.
V. Cross-Domain and System-Level Considerations	21	Integration of AI with real-time energy monitoring software can optimize plant-wide energy efficiency.
	22	Sustainability by design needs to guide all digitalization initiatives (AI, IoT, robotics) in auto-production.
	23	Human-centric design and ethical AI governance are the prerequisites for Industry 5.0 responsible implementation.
	24	Resilience and sustainability must be integrated not only in manufacturing, but also in the upstream research and development and design chains.
	25	Tomorrow's automotive plants must have interdisciplinary cooperation (engineers, data scientists, ethicists, and policy-makers).

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