Improving the Performance of Manufacturing Supply Chains in Industry 5.0: An Analysis Using Fuzzy-topsis Approach

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Abstract

As the latest industrial revolution, Industry 5.0 has the potential to profoundly reshape the design and management of supply chains in multiple ways, such as to make the supply chain more human-focus, sustainable, and flexible. This offers opportunities for organisations to promote their business competitiveness. While the adoption of Industry 5.0 is gaining momentum in the manufacturing sector, there exists a risk of failure and being locked into ineffective strategies during the transition. Despite this pressing need, research on Industry 5.0 remains in early stage. Particularly, there is a lack of adequate discussion on how to evaluate manufacturing supply chain performance in the context of Industry 5.0. This paper aims to enhance supply chain performance by identifying a comprehensive list of performance indicators and prioritising potential solutions and alternatives based on their levels of significance. A multistep research methodology was adopted in this study, including (1) using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method to identify a comprehensive list of key performance indicators and alternative solutions to improve manufacturing supply chain performance in Industry 5.0; (2) collecting survey data from three industry professionals to quantify the level of significance of the identified alternatives; and (3) applying the fuzzy Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to prioritise the identified alternatives. The study identified a total of 28 indicators and four potential alternatives for improving manufacturing supply chain performance in Industry 5.0. The findings reveal that the implementation of a real-time operational framework, the promotion of transparency and information sharing among supply chain partners, and the leveraging of advanced technologies are the most significant alternatives in this regard. This paper contributes to the existing body of knowledge by providing a foundational foothold for researchers and industry practitioners to make informed strategic decisions pertaining evaluation of and

improvement in supply chain performance, further enhancing companies' competitiveness, profitability, and sustainability in the era of Industry 5.0.

Keywords: Industry 5.0, manufacturing supply chains, fuzzy-TOPSIS, performance indicators, human-centric manufacturing, real-time operations, multi-criteria decision-making, supply chain resilience

1. Introduction

Industry 5.0 reframes the aims of industrial transformation around human-centricity, sustainability, and resilience whilst retaining the digital foundation inherited from Industry 4.0 (Breque et al., 2021; Choi et al., 2022). In supply chains, this reorientation implies that performance cannot be judged solely on cost and speed, because it also includes flexibility, environmental and social outcomes, and the capacity to sense and respond in real time (Ahmed et al., 2023; Birkel & Müller, 2021). Recent work converges on this transition and argues for systems that pair human creativity with machine intelligence, treating worker wellbeing as a design constraint rather than an addition (Kaasinen et al., 2022; Romero & Stahre, 2021).

Despite the clarity of this impetus, organisations face practical uncertainty about which interventions should be prioritised to deliver measurable performance gains in Industry 5.0 conditions. Studies indicate that information sharing and visibility improve collaboration, agility, and supply chain performance, especially under disruption, whilst IoT-enabled tracking and analytics underpin resilient responses (Ahmed et al., 2023; Baah et al., 2022; Ivanov, 2023). Moreover, decision-making has to contend with linguistic judgements and incomplete data (Choudhary et al., 2021). Fuzzy multi-criteria decision-making methods address these realities in a transparent manner that practitioners can apply (Al-Mhdawi, O'Connor, et al., 2023; Al-Mhdawi, Qazi, et al., 2023; Chen et al., 2020; Stević et al., 2020).

Drawing on this context our paper responds to the early-stage nature of Industry 5.0 research through a PRISMA-guided scoping of indicators and alternatives, a small expert elicitation, and a fuzzy-TOPSIS prioritisation. Our aim is to offer a replicable, decision-focused approach rather than a definitive ranking. We inform our analysis with adjacent work on data maturity, decision rights, and governance in complex programmes, which shows how organisational conditions can amplify or dull the benefits of seemingly promising digital initiatives (Barber et al., 2021; Baxter et al., 2023; Brookes et al., 2020).

2. Human-Centric, Digital, and Analytical Foundations of Industry 5.0 Supply Chains

Industry 5.0 positions human-centric design, resilience, and sustainability as co-equal aims for industrial systems and, by extension, for the supply chains that support them (Breque et al., 2021; Choi et al., 2022). Human-centric manufacturing emphasises safety, ergonomics, cognitive support, and meaningful work. Advocates describe a progression in human–machine relations from coexistence and cooperation to compassion and coevolution (Nahavandi, 2019; Romero & Stahre, 2021). This perspective implies that performance indicators should extend beyond cost and speed to include environmental and social outcomes, together with the digital and relational enablers that permit real-time decisions.

Empirical research further associates these practices with collaboration, agility, and improved performance, especially in unstable conditions, which suggests that transparency is a material priority rather than a complementary extension (Baah et al., 2022; Bayraktar et al., 2020). Agile approaches have been shown to enhance flexibility, adaptability, and responsiveness in complex and uncertain circumstances, particularly when integrated with digital transformation initiatives (Dong et al., 2022; Zhang et al., 2023). The resilience demonstrated through agile practices during disruptive events underscores their value in contemporary supply chain contexts (Al-Mhdawi, Dacre, et al., 2023; Dacre et al., 2019; Dong et al., 2021b; Sonjit et al., 2021). These effects have been reported using survey-based structural models that explicitly link visibility, collaboration, and agility to performance outcomes. A complementary experimental stream examines distributed ledgers and shared data layers (Chen et al., 2021). Simulation and testbed studies indicate that blockchain can address information asymmetry, strengthen data integrity, and support auditable traceability, provided that integration costs, liability, and incentives are carefully balanced.

Digital technologies associated with Industry 5.0 form a second stream. IoT sensing, control via 5G connectivity, and digital twins shorten the sense–decide–act loop by turning production events into actionable information (Choi et al., 2022; Fraga-Lamas et al., 2022; Gong et al., 2022; Longo et al., 2019). Studies highlight that, in post-pandemic contexts, real-time tracking and analytics are repeatedly prioritised as top imperatives for resilient performance, a finding that coheres with the rank order in our studyn (Ahmed et al., 2023; Ivanov, 2023). Additionally, human–robot collaboration and augmented work expand this logic beyond data flows into the design of work systems. Here, quality and wellbeing metrics for human–robot interaction are moving from conceptual discussion toward operational measurement, which is consistent with the Industry 5.0 ambition to combine productivity with human outputs (Casalino et al., 2021; Kaasinen et al., 2022). The emerging context is of a socio-technical architecture where data latency, visibility, and human augmentation reinforce one another.

Performance frameworks provide the bridge from concepts to operationalisation. Legacy approaches such as the SCOR model remain useful scaffolds, although they are being extended to include digitalisation and sustainability as first-class concerns (Ayyildiz, 2021; Ayyildiz & Taskin Gumus, 2021; Dong et al., 2021a; Tite et al., 2021a, 2021b). Proposals labelled SCOR 4.0, sometimes further adapted for resilience or green supply chains, introduce new attributes and metrics and then determine their relative importance using fuzzy or hybrid MCDM methods (Choudhary et al., 2021; Lima-Junior & Carpinetti, 2020). Within an Industry 5.0 context they highlight how to embed digital and environmental outcomes within an established performance architecture rather than bolting them on after the fact. Similar extensions appear in sectoral applications, for instance in e-waste and floriculture, which demonstrates the feasibility of tailoring an augmented SCOR to different contexts whilst maintaining comparability.

A third stream concerns decision support under uncertainty. Industry 5.0 choices typically involve many criteria and stakeholders, with evidence that is emergent, fragmented, or expressed in linguistic terms. Fuzzy MCDM methods accommodate this reality by combining interpretability with accuracy (Chen et al., 2020; Pamucar et al., 2022; Stević et al., 2020). Artificial intelligence and machine learning approaches are also increasingly being explored to support project prediction and decision-making in complex environments supported by novel learning mechanisms (Dacre et al., 2022; Dacre et al., 2018; Dacre & Kockum, 2022; Dacre et al., 2020; Gkogkidis & Dacre, 2020, 2021, 2023; Hsu et al., 2021). Variants of fuzzy-TOPSIS have been applied to green and resilient supply chains to produce closeness coefficients that are easy to communicate to practitioners, whilst fuzzy Best–Worst methods provide structured means of eliciting criteria weights. Recent studies calibrate fuzzy BWM to disruption contexts, strengthening the case for formal multi-criteria approaches in volatile environments. This analytics thread also connects to organisational factors, such that reviews of project data analytics and studies of governance in complex programmes argue that data definitions, decision rights, and institutional constraints often decide whether analytics translate into performance (Dacre & Kockum, 2022; Kockum & Dacre, 2021). These insights are increasingly imported into supply chain control towers and digital operations initiatives, which reinforces the need to pair technology investments with governance reforms (Baxter et al., 2023; Brookes et al., 2020).

3. Methodology

In lieu of the research context outlined, we adopt a three-stage design that aligns with the developmental aims of our paper. A PRISMA-guided review identifies performance indicators aligned with Industry 5.0 and a set of improvement alternatives (Breque et al., 2021; Romero & Stahre, 2021). An expert elicitation captures the relative importance of indicators and the expected impact of alternatives under linguistic scales. A fuzzy-TOPSIS procedure then aggregates expert views, determines distances from positive and negative ideal solutions, and produces closeness coefficients for a ranked set of alternatives.

In the first stage, we targeted peer-reviewed articles and significant reports on human-centric manufacturing, resilience and sustainability, digital and data-driven supply chains, and fuzzy MCDM in manufacturing contexts. Sources included European policy framing of Industry 5.0, human-centric operations studies, and decision-analytic applications in supply chains (Breque et al., 2021; Chen et al., 2020; Choi et al., 2022). Our synthesis produced 28 indicators and four alternatives that map onto the Industry 5.0 agenda whilst remaining compatible with extended SCOR logic.

For the second stage, our expert panel comprised three manufacturing supply chain practitioners with more than a decade of experience in operations planning, digital transformation, or sustainability. Using a five-point linguistic scale ranging from very low to very high, experts assessed the importance of the 28 indicators and the expected impact of the four alternatives on each indicator. We mapped linguistic terms to triangular fuzzy numbers in [0, 1] following standard practice, which preserves nuance without demanding spurious numerical precision (Choudhary et al., 2021; Stević et al., 2020). The small panel is consistent with early-stage applications where the purpose is to demonstrate a tractable process under high uncertainty before escalating to larger Delphi exercises (Buckley, 1995; Habibi et al., 2014; Niederberger & Spranger, 2020).

In the final analytical stage, we aggregated the judges' ratings in a fuzzy decision matrix. Benefit indicators were normalised by division through the maximum value, whilst cost indicators were inverted before normalisation. We derived indicator weights from importance ratings via the centroid method and normalised them to sum to 1.0. For each indicator, we constructed a fuzzy positive ideal solution and a fuzzy negative ideal solution, computed distances by the vertex method, and calculated closeness coefficients as the share of distance from the negative ideal over the sum of distances (Chen et al., 2020; Stević et al., 2020). To ensure accuracy, we explored perturbations through ±10% variations of indicator weights and a leave-one-expert-out sensitivity test. Our choice of TOPSIS reflects its interpretability for practitioners and established usage in supply chain decision problems where uncertainty and linguistic judgements dominate.

4. Initial Findings

Our indicator set covers five domains consistent with the Industry 5.0 agenda. Operational performance, flexibility and responsiveness, sustainability, human-centric outcomes, and digital or relational enablers. Operational measures include on-time delivery, order fulfilment, lead time, schedule adherence, and quality defects. Flexibility and responsiveness include changeover time, mix and volume flexibility, and responsiveness to shocks. Sustainability encompasses energy and waste intensity, emissions per unit, recycling rate, and circular material use. Human-centric measures include lost-time injury frequency, ergonomic risk, training hours, and perceived workload balance. Digital and relational enablers include visibility, interoperability, data latency, information sharing frequency, partner trust, cyber incidents, and digital twin maturity.

When we applied the fuzzy-TOPSIS analysis, a clear ordering of alternatives emerged. Implementing a real-time operational framework obtained the highest closeness coefficient at 0.71, followed by promoting transparency and information sharing at 0.66, leveraging context-appropriate advanced technologies at 0.63, and investing in workforce augmentation and human-centric redesign at 0.58. Notably, the top two positions remained invariant to ±10% weight perturbations and to leave-one-expert-out tests, whilst the third and fourth occasionally swapped at extreme settings.

Examining the underlying drivers, experts attributed the largest weighted gains under the real-time framework to improvements in visibility, data latency, responsiveness to demand shocks, on-time delivery, and schedule adherence. Transparency and information sharing primarily improved partner trust, plan stability, and order fulfilment. Advanced technologies delivered targeted gains in quality, waste reduction, and flexibility, although the impact depended on process integration and people skills (Dacre et al., 2021; Eggleton et al., 2021).

5. Discussion

Our ordering of alternatives suggests a practical sequence for building capabilities. A real-time operational framework provides the nervous system that shortens the sense–decide–act loop (Ahmed et al., 2023; Choi et al., 2022). Subsequently, transparency and information sharing ensure that decisions propagate across firm boundaries and that partners resolve shared constraints quickly. Technology investments then amplify these foundations when embedded in redesigned routines and roles, which is consistent with performance guidance that explicitly links indicators to technologies and with decision-analytic evidence on calibrating priorities in volatile contexts.

Furthermore, organisational conditions moderate the returns to digital investment (Barber et al., 2021; Baxter et al., 2023; Brookes et al., 2020). Reports and studies connected to project and programme settings show that data governance, decision rights, and institutional constraints can create process paralysis or enable fast, accountable action. The implication for supply chains is that control towers should have clear role definitions, human-in-the-loop decision support, and benefits realisation that values resilience and sustainability alongside efficiency (Brookes et al., 2020; Eggleton et al., 2023). This perspective reframes human-centric outcomes as integral performance targets that influence quality and responsiveness rather than compliance items. In practice, the design task is to codify what data to share, at what latency, and under what controls, then enlarge the shared envelope as trust and value accrue, a stance supported by blockchain testbeds and simulation studies (Chen et al., 2021).

Finally, our findings reinforce the usefulness of fuzzy MCDM as a bridge between emergent evidence and operational decision-making (Ayyildiz, 2021; Lima-Junior & Carpinetti, 2020). The closeness coefficients provide a defensible starting point for investment sequences, whilst sensitivity tests clarify where rankings are stable and where local context may tip the balance. As organisations extend measurement systems toward Industry 5.0 aims, augmented SCOR models and calibrated weighting methods can help maintain coherence between strategic goals, operational metrics, and the governance required to sustain change.

6. Conclusion

In this paper, we sought to identify an Industry 5.0-aligned indicator set and prioritise performance-improvement alternatives for manufacturing supply chains using fuzzy-TOPSIS. Our analysis suggests that building a real-time operational framework and promoting transparency and information sharing are the most consequential early moves. Targeted technology deployments and human-centric redesign then add further value once the system foundations are in place. These findings are consistent with broader evidence that emphasises IoT-enabled tracking, visibility, collaboration, and human-centred operations as pillars of resilient performance (Ahmed et al., 2023; Baah et al., 2022; Romero & Stahre, 2021).

As an exploratory study with a small expert panel, external validity is necessarily limited. Fuzzy-TOPSIS helps encode linguistic judgements and generate interpretable priorities, although results remain sensitive to indicator weights and panel composition. Nevertheless, the stability of the top two alternatives across sensitivity checks is encouraging, as it points to system-level levers with cross-context traction.

Going forward, we aim to expand our expert pool and employ Delphi-based consensus building to refine the indicator set. We will also compare fuzzy-TOPSIS with alternatives such as BWM–VIKOR and MARCOS in this context, drawing on established applications in supply chains and disruption settings (Ayyildiz, 2021; Pamucar et al., 2022; Stević et al., 2020). In future research, we will link indicator movement to longitudinal performance data and examine sector-specific tailoring. We will pay particular attention to governance and decision rights in control-tower designs, extending prior work on data analytics maturity and the organisational dynamics that affect the translation of digital capabilities into outcomes (Baxter et al., 2023; Brookes et al., 2020; Reynolds & Dacre, 2019).

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