



A Behaviourally Informed Heuristics-Framework for Net Zero Transformation in Manufacturing

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Abstract. Transitioning to net zero emissions in manufacturing is fraught with challenges, from navigating uncertainties and making critical trade-offs, to overcoming biases and information asymmetry. Such behavioural challenges could potentially result in bounded rationality, where decision-makers operate under limited information and cognitive constraints. This paper introduces a framework that employs behaviourally informed heuristics to simplify the complexity of net-zero transformation. By incorporating behavioural model of rational choice and decision-making rules, the framework could help manufacturing decision-makers to manage uncertainties and cognitive limitations, thus broadening the toolkit for navigating the reduction of carbon emissions.

Keywords: Net zero manufacturing · Transformational framework · Bounded rationality

1 Introduction

The manufacturing sector plays a pivotal role in driving economic growth and development worldwide. However, its contribution to greenhouse gas emissions and environmental degradation has raised concerns about its long-term sustainability. As the global community intensifies efforts to combat climate change, the transition towards net-zero emissions in the manufacturing sector has become a critical imperative. This research paper explores the behavioural, cognitive, and organizational challenges associated with the net-zero transformation in the manufacturing sector. Resistance to change due to high costs, long investment cycles, and concerns about disrupting systems hinder the adoption of low-carbon technologies and processes, especially in energy-intensive industries fearing non-performance impact on production and low implementation of energy efficiency projects [1–3]. Overcoming this requires organizational culture shift, management commitment, employee engagement [4–6]. Lack of awareness, knowledge, skills among employees and managers [7–9] necessitates continuous education, training, knowledge transfer [10]. Aligning business-sustainability goals, fostering digital

transformation environment is crucial [6, 9, 10]. Short-term thinking, competing priorities constrain decarbonization strategies [11]. Trade-offs between economic gains-sustainability goals, resource constraints hinder net zero transition [8, 12]. Stakeholder engagement, collaboration engaging industrial communities to overcome resistance [13], industry-wide cooperation, sustainable value chain practices [14–16] is vital. Regulation, policy support like mandates, incentives can motivate shift from linear to circular approaches [1, 17, 18], but effectiveness depends on ambition level, company capacity, with greater challenges for smaller, energy-intensive firms [19]. To address these challenges, the paper presents a comprehensive review of existing models and frameworks for guiding the net-zero transformation and proposes a behaviourally informed strategic decision making. It critically evaluates current state of the art's strengths and limitations, highlighting the need for more holistic and adaptive approaches that integrate technological, economic, social, and behavioural dimensions to facilitate the transition towards a sustainable and resilient future.

2 Literature Review

2.1 Behavioural Challenges in Net Zero Manufacturing Transformation

The transition to net-zero manufacturing faces several behavioural challenges, as highlighted in multiple studies and summarised below in this section. Resistance to change emerges as a prominent obstacle, with employees and management often reluctant to adopt new technologies and practices [7, 12, 20]. This resistance is particularly evident in industries with long-established processes and infrastructures, such as the steel industry [7]. The lack of awareness, insufficient skills, and the discomfort caused by new net-zero practices further exacerbate this resistance [10, 12]. Organizational culture and leadership play important roles in overcoming these behavioural barriers. Studies emphasize the importance of top management commitment, continuous training programs, and the development of a sustainability-driven culture [10, 12]. The need for significant shifts in organizational behaviour and mindset is highlighted, particularly in aligning business objectives with sustainability goals [8, 22]. This cultural shift is essential for fostering an environment that supports and encourages sustainable practices and innovation. The challenge extends beyond individual organizations to industry-wide adoption of sustainable practices and innovative technologies [16, 23]. Many studies point out that achieving net-zero emissions will require significant changes in manufacturing processes and the adoption of new technologies by stakeholders across the value chain [16, 23]. This necessitates a collective effort and a shared commitment to sustainability goals, which can be challenging to cultivate across diverse industry participants. Overcoming these behavioural challenges requires coordinated efforts, supportive policies, and a commitment to long-term sustainability goals from all stakeholders involved in the manufacturing sector [10, 24]. The importance of employee engagement and training is frequently emphasized, as is the need for clear communication and collaboration between different sectors of the industry [12, 17]. Additionally, addressing concerns about job displacement and the potential economic impact of the transition is crucial for gaining widespread support and minimizing resistance to change [12, 22]. By addressing these behavioural challenges comprehensively, the manufacturing sector can navigate

the complex path towards net-zero emissions. The behavioural challenges on the net zero journey in manufacturing can be summarized below in Table 1 in three categories of impact on decision making, namely complexity, information asymmetry and cognitive biases. These challenges compounded with the time bound pressure of achieving net zero goal contributes to bounded rationality.

Table 1. Summary of key behavioural challenges

Category	Challenges	References
<i>Complexity</i>	High-emitting, fossil fuel-dependent infrastructures	[20, 25]
	Fundamental shifts in technologies, processes, and raw materials	[12, 26]
	Integration of renewables and energy efficiency	[11, 27]
	Multiple stakeholder involvement	[28]
	Diverse company characteristics	[29]
	Multi-sector, multi-region coordination	[13]
<i>Information Asymmetry</i>	Lack of accurate, comprehensive data	[20, 25, 26]
	Historical underreporting and underestimation of emissions	[27]
	Communication difficulties with broader audiences	[30]
	Challenges in integrating and analysing vast amounts of data	[29]
	Data availability, reliability, storage, and processing issues	[13]
<i>Cognitive Biases</i>	Status quo bias leading to resistance to change	[11]
	Short-term focus hindering climate change responses	[28]
	Underestimation of long-term decarbonization benefits	[20, 25, 28]
	Confirmation bias in seeking information	[20, 25]
	Herding influencing adoption of sustainable practices	[29]
	Anchoring effect on cost estimates and targets	[13, 24]

2.2 Net Zero Manufacturing Transformation Models

The transition to net-zero emissions in manufacturing has led to various models and frameworks for this transformation. While providing insights, these models have limitations. The technology roadmap by [26] outlines a framework for net-zero emissions in emissions-intensive industries by 2050, emphasizing innovation-supporting policies and decarbonization. However, it assumes perfect rationality and does not address behavioural challenges or resistance to new technologies. Models integrating organizational and technological dimensions, like the ADO framework [21] and the theoretical model in [26], highlight enablers and barriers to decarbonization but often miss the

complex stakeholder interrelationships and unintended consequences. Specific models like VENRA [31] for shipyard performance and I4.2-GiM [4] for integrating manufacturing with energy management offer structured approaches but lack generalizability. Roadmaps and step-by-step approaches, such as the bio steel cycle [1] for the steel industry and the Integrated Systems plus Principles Approach [3] for net-zero manufacturing, provide practical guidance but often rely on assumptions about technology availability and cost-effectiveness, overlooking economic and regulatory barriers. Sector-specific models for industries like cement [27], chemical and process [28], offer insights but ignore the interconnectedness between sectors and the need for a holistic approach. Many models fail to address social and behavioural dimensions, such as resistance to change, stakeholder engagement, and local contexts [13]. Models focusing solely on technological solutions and economic incentives may miss the complex decision-making processes and the role of values, culture, and emotions in adopting sustainable practices. The review of the current state of the art in various models and frameworks for net-zero emissions transformation in manufacturing reveals several limitations that can be summarised below in Table 2.

Table 2. Summary of limitations of current state of the art

Challenge	Description
Rationality Assumption	Many models assume perfect rationality in decision-making, overlooking the cognitive biases and behavioural challenges that can hinder the adoption of new technologies
Complexity Oversimplification	Frameworks like ADO and other theoretical models often fail to capture the full complexity of stakeholder interactions and potential unintended consequences of decarbonization efforts
Limited Generalizability	Sector-specific models provide structured approaches but may lack applicability across diverse industrial contexts
Technological Optimism	Step-by-step approaches tend to rely on optimistic assumptions about technology availability and cost-effectiveness, potentially underestimating economic and regulatory barriers
Sectoral Silos	Industry-specific models for cement, chemical, and electronics often neglect the interconnectedness between sectors, missing opportunities for synergistic solutions
Social Dimension Gap	Many models inadequately address social and behavioural aspects, including resistance to change, stakeholder engagement, and local contextual factors
Holistic Perspective Lacking	Tendency to focus on technological solutions and economic incentives, overlooking the complex decision-making processes and the role of values, culture, and emotions in driving sustainable practices

These findings highlight the need for more comprehensive, interdisciplinary approaches that integrate technological, economic, social, and behavioural dimensions to effectively guide the transition to net-zero emissions in manufacturing.

3 Discussion

Bounded rationality is the idea that when individuals or firms make decisions, they do so in a way that is purposeful but limited by constraints, rather than being fully informed and perfectly rational [31]. The concept was pioneered by Herbert A. Simon, who identified three key constraints on decision-making [32]. Firstly, only limited and often unreliable information regarding the alternatives and their consequences is available; the human mind has a limited ability to evaluate and process the available information; time constraints limit the ability to make decisions [33]. These factors contribute to bounded rationality for individuals. In organizations and firms, an inability to adequately deal with these constraints can lead to analysis paralysis and impaired decision-making. The behavioural model of rational choice that Simon put forth involved several key elements [34] – The set of all possible behaviour alternatives, subset of those alternatives considered by the individual, possible outcomes of each choice, pay-off function representing the value placed on each outcome, information (complete or incomplete) about which outcomes will occur for each choice and probability information for each outcome. Bounded rationality recognizes the real-world limitations and constraints on decision-making that make perfect rationality impossible [33]. Instead, individuals employ approximate methods compatible with the information, cognitive abilities, and time available to them. Understanding these methods can provide insight into how decisions are made by both individuals and organizations. In this research work, a behavioural model of rational choice has been made to support strategic decision making in net zero manufacturing transformations. This research work presents a conceptual framework that includes all the elements suggested by Simon in any behavioural model of rational choice. The framework begins with a list of all the decisions organisations need to take on their net zero journey as identified in literature and summarised below in Table 3 along with the heuristics to be mindful of while making these decisions.

Table 3. Decisions and heuristics on net zero journey.

Decision	Heuristics	Challenge being tackled	References
Technology Adoption	Select low-carbon technologies, weighing perceived costs and disruption against long-term benefits	Cognitive Biases	[6, 7, 9, 11]
Data Management and Transparency	Establish robust systems for accurate data collection and reporting to ensure transparency, reliability, and informed decision-making	Information Asymmetry	[12, 21, 26, 27]

(continued)

Table 3. *(continued)*

Decision	Heuristics	Challenge being tackled	References
Stakeholder Engagement	Develop strong communication and collaboration strategies with all stakeholders, including co-producing decarbonization strategies with local communities for acceptance and success	Complexity	[13, 29]
Organizational Culture	Foster a sustainability-driven culture through leadership commitment, continuous training, and alignment of business objectives with sustainability goals	Cognitive Biases	[10, 22, 23]
Resource Allocation	Allocate resources, especially for SMEs, balancing investments in tangible assets, skills, culture, and knowledge management	Cognitive Biases	[10, 30]
Supply Chain Restructuring	Adopt circular economy principles, which requires significant restructuring of supply chains, product design, and end-of-life management	Complexity	[29, 31]
Energy Management	Integrate renewable energy sources and improve energy efficiency through sophisticated optimization and management. Consider on-site renewable energy systems where feasible	Complexity	[28]

(continued)

Table 3. (continued)

Decision	Heuristics	Challenge being tackled	References
Policy Engagement	Actively engage with policymakers to support the development of robust policy frameworks and financial incentives. Stay informed about evolving regulations and carbon pricing mechanisms	Cognitive Biases	[2, 10, 23, 25]
Long-term Planning	Develop strategies that account for the long-term impacts of climate change and decarbonization efforts, avoiding short-term focus	Cognitive Biases	[11, 29]
Innovation and R&D	Invest in research and development of new technologies and processes that can significantly reduce emissions, such as carbon capture and storage or alternative materials	Cognitive Biases	[1, 25]
Performance Measurement	Implement comprehensive performance measurement frameworks that integrate environmental, social, and economic factors	Information Asymmetry	[31]
Risk Assessment	Conduct thorough risk assessments, considering both the risks of inaction and the potential challenges of implementing new technologies and practices	Cognitive Biases	[31], [41]

The heuristics identified from the literature review and summarised above can potentially support in limiting if not overcoming bounded rationality. The framework shown below in Fig. 1, does not have rationality assumption, in fact it is based on acknowledging its presence. The complexity is not oversimplified, rather it is accounted for by starting with a wide variety of decisions that could have a potential impact on overall progress. The framework is not sector specific and can be deployed in across manufacturing industry. It considers the entire manufacturing systems as the scope and also accounts for sector specific challenges in the second step with information and probability assessment.

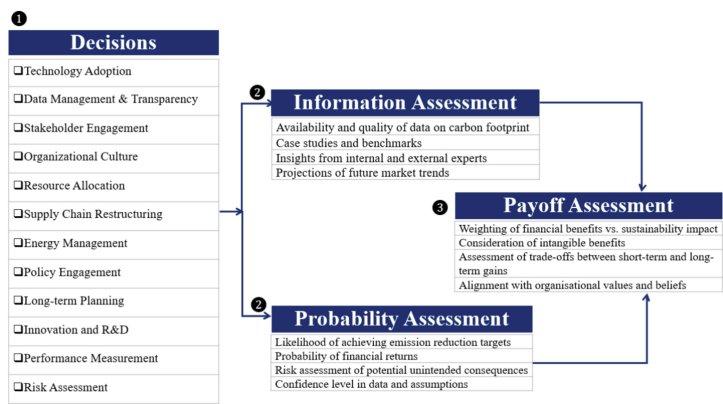


Fig. 1. Behavioural model of rational choice for net zero manufacturing.

4 Conclusion

This research paper delves into behavioural challenges, highlighting resistance to change, information asymmetries, cognitive biases, and the need for adaptive transformation models. The behavioural model of rational choice for net zero manufacturing transformation offers a framework for organizations to make better decisions for achieving net-zero emissions. By systematically evaluating choices, outcomes, and assessments, businesses can navigate sustainability complexities and ensure long-term success in a low-carbon future. However, this research has limitations. The proposed framework is based on existing literature and may not fully capture specific industrial contexts or regional variations. Rapid technological advancements and changing market dynamics may require periodic updates to the model. Future research should focus on empirical studies and case analyses to validate and refine the model. Practical insights from industry stakeholders and policymakers would enhance the model’s applicability and relevance. Overall, this research supports efforts to decarbonize manufacturing and encourages further exploration and collaboration among researchers, policymakers, and industry professionals to accelerate the transition to a sustainable future.

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