Proceedings of the 8th European Conference on Industrial Engineering and Operations Management
Paris, France, July 2-4, 2025

Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/EU08.20250228
Published: July 2, 2025

Developing a Framework to Improve Supply Chain Resilience Strategies for Offshore Wind Energy Organizations using a Circular Economy Approach

Emeka Nwonu, Jose Eduardo Munive-Hernandez and Cuong Dao
Faculty of Engineering & Digital Technologies
University of Bradford
Bradford, BD7 1DP, United Kingdom
E.J.Nwonu@bradford.ac.uk, J.E.Munive@bradford.ac.uk. D.C.Dao@bradford.ac.uk

Abstract

The UK offshore wind (OSW) sector is growing at an accelerated rate due to rising environmental, social and political concerns. The British Energy Security Strategy was established in 2022 with the aim to decarbonize the UK electricity system by 2030 through investments in renewable energy, emphasizing support to local supply chain to accelerate the transition. Thus, the offshore wind industry will continue to grow. However, the new growth target and localized supply chain initiatives also raise sustainability challenges. The current economic system characterized by the linear model (conceive, extract, produce, use, and dispose) is unsustainable. Therefore, the circular economy (CE) model offers the opportunity for a more sustainable alternative. This paper proposes a practical framework to identify key functional areas to help formulate more effective and resilient supply chain strategies for the offshore wind industry. The proposed approach is based on the strategy wheel (visual framework), emphasizing resilience at its core and incorporating the 3R principles of circular economy (Reduce, Reuse and Recycle). The proposed framework can help organizations move from a one-size-fits-all approach towards more coordinated and effective resilience strategies to enhance supply chain performance. The paper focuses on the UK offshore wind industry and provides relevant insights to better understand the complexity of its supply chain, its relationships with sustainability strategies and key factors affecting overall supply chain performance. The study highlights the necessity of integrating 3R principles into resilience strategies for supply chains and asserts that the 3R principles are fundamental building blocks for achieving sustainability.

Keywords
Supply Chain Resilience, Circular Economy, 3R Principles, Offshore Wind, Strategy Wheel.

1. Introduction
Global greenhouse gas (GHG) emissions set a record of 57.1 Gigatonnes of Carbon Dioxide Equivalent (GtCO2e) in 2023, a 1.3% increase from 2022 levels (UNEP 2024). The increase of 1.3% is above the average rate in the decade preceding the COVID-19 pandemic (2010–2019) when GHG emissions grew at an average rate of 0.8% per year. The current trajectory forecasts a temperature rise of an average of 2.6–3.1˚c by the end of the century, and if efforts to reduce GHGs do not increase, it will bring debilitating impacts to people, the planet and economies. Consequently, a shift in the energy mix to renewable sources is important to mitigate the threat of climate change and ensure a sustainable future (Pani et al. 2022). The scale of the climate challenge is daunting but there are opportunities for accelerating the mitigation.

Technology developments, particularly in wind and solar energy continue to exceed expectations, lowering deployment costs and driving their market expansion. The offshore wind (OSW) technology has become a preferred choice (Velenturf, 2022). Wind is considered an important source of green electricity production which helps fight against climate change, and its installation has increased at an exponential rate (Zied et al. 2022), which means it is becoming a major element of the power mix. In 2023, the power sector continued to be the leading contributor to emissions at 15.1 $GtCO_2e$ (UNEP 2024). Therefore, reducing emissions in this sector is fundamental towards meeting current global warming targets of 1.5˚c by 2030. The importance of this and similar studies cannot be overemphasized as a changing climate can influence shifts in energy supply and demand due to climate induced needs for cooling, increase in wildfires events, increase in emissions from agriculture and subsequent increased irrigation and agrochemical needs (Yang et al. 2024).

Moreover, the global natural ecosystem is shrinking in size and volume, and the current traditional linear model (conceive, extract, produce, use, and dispose) that is the core of the modern economic system is unsustainable (Korhonen et al. 2018). Resource depletions are increasingly challenging the well-being of humans, animals and the biosphere at large (Meadows, 2013), in the form of hurricanes, droughts, heat waves, increase in poverty and global hunger, forest fires and pandemics (Oliveira et al. 2021). These issues highlight the vulnerability of the current linear development paths and emphasize the need for alternative novel approaches (Morrissey et al. 2022). The circular economy (CE) presents a new practical approach to sustainable development (Ma et al. 2021).

The UK offshore wind sector is growing at an accelerated rate due to rising environmental, social and political concerns. This has led to the development of the British Energy Security Strategy in 2022 with intent to decarbonize the UK electricity system by 2030 through investments and initiatives in the renewable energy with emphasis on the local supply chain to support and accelerate the transition. With an ambitious target of reaching 50 Gigawatt (GW) by 2030 from 14.9GW in 2022 (+300%), the UK OSW industry will continue to grow. However, the new growth target and localized supply chain initiatives raise new sustainability challenges.

This purpose of this paper is to propose a strategic framework to identify key organizational functional perspectives to help formulate more effective and resilient supply chain strategies for the OSW industry and the supporting activities required to ensure successful strategy implementation. The proposed approach is based on the strategy wheel (practical visual framework), emphasizing resilience at its core and incorporating the 3R principles of CE (Reduce, Reuse and Recycle). While high level strategies like the 3Rs, 7Rs, circular strategies and closing the circular economy loop in general have been largely explored, there is a shortage of implementation frameworks for implementing these in the OSW sector. Furthermore, most strategies emphasize the primary tasks in the SC without much consideration for the supporting tasks which are a very crucial factor in the success or failure in the execution of the strategy. This framework offers an opportunity both in theory and practice for considerations of the supporting tasks during strategy formulation and implementation phases respectively.

1.1 Objectives

The following objectives were set for achieving the purpose of this study:

- Identify key OSW supply chain stages.
- Development and application of the strategy wheel framework.
- Integration of the CE principles to enhance resilience strategies.

The structure of the paper considers the relevant literature review, a discussion of the research methodology, the development of the circular strategy wheel framework, the discussion of results, findings and limitations, and recommendations for future research.

2. Literature Review

The circular economy (CE) is a model of production and consumption which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible (European Parliament 2023). CE is an industrial system that is regenerative and restorative by intention and design (Ellen MacArthur Foundation, 2015 a), which offers an opportunity to extend the lifecycle of products. Three main principles of the CE are to control finite stocks and balance natural resource flows, maximize utility and improve resource benefits through the promotion of product and materials recycling, and to improve system efficiency through a reduction of material and energy losses through the circular system (Ellen MacArthur Foundation, 2015 b). The definition of CE was further expanded beyond the 3Rs by Ma et al. (2021). They suggested that CE refers to the redistribution of waste and the notion of multiple circular setups to increase the value added of products through processes and activities that include Redesigning, Reusing, Recycling, Remanufacturing, Redistribution of waste products and/or prolonging product life through effective maintenance. These complementary principles highlight opportunities for enhanced circularity methods beyond the traditional 3Rs of Reduce, Reuse and Recycle, further expanding the scope of CE.

The supply chain is described as all the activities associated with creating and distributing goods and or services. According to Pellicelli (2022), the supply chain encompasses all the activities and processes involved in delivering products and services, from sourcing raw materials and parts, procurement, manufacturing and assembly, logistics, warehousing through to the distribution and sale to the customers and end-users, including the management and information systems required to monitor all these activities across the various steps. A supply chain may comprise different businesses across different tiers (Beamon 1998). Scholars have defined supply chain from varying perspectives ranging from Product flow from upstream to downstream (Pineear 2009), linkage and connection between producers and ultimate end consumers who benefit from using the product (Dutta and Hora 2017). Wu et al (2016) took an efficiency perspective and defined supply chain as receiving the right products in the right quantities, at the right time, in the right location for the right cost to the satisfaction of the right customer. From an analysis of the above definitions and perspectives, it is sufficient to describe supply chain as all the efforts and infrastructures connected and working together towards efficiently delivering value for all stakeholders across the supply chain.

A resilient supply chain is one that can easily adapt, rebound or recover when faced with economic shocks that are either idiosyncratic such as local supplier issues and closure or systemic like natural disasters or pandemics like Covid-19 (Behzadi et al., 2020; Singh et al., 2023). Ivanov (2018) provided a more expansive definition suggesting that resilience does not only provide an ability for a supply chain to withstand use corrective actions to adapt decisions and restore performance to its original state when under disruption but also gives it the ability to move to a new and more desirable state. This suggested that resilience is not just the ability to recover to original state, but the ability to function under stress and adapt to changing conditions as required. Therefore, it can be argued that supply chain resilience (SCRes) factors would include robustness which is an ability to function when not in equilibrium, and flexibility or dynamism to adapt and morph as required to effectively handle and manage changing conditions. Supply chain strategies can be grouped under two broad categories: demand side strategies focused on improving benefits for the customer, and the supply side improvements focused on operations (Morash 2001). There is a general agreement that circular supply chains differ from linear supply chains but processes and performance measures that holistically constitute a circular supply chain have not been extensively researched empirically. Sassanelli et al. (2019) suggested that different circular models focus on different perspectives such as economic, legal and environmental at different stages of the product or access life cycle such as beginning of life, middle of life or in use, and end of life.

The strategy wheel is a practical visual framework proposed by Mongomery (2012) to help define and document how a system of value creation (such as a supply chain) can be effectively integrated (through different organizational functions or perspectives) to support achieving the long-term purpose of an organization (strategic goals). The purpose of the organization should be at the heart of the strategy of the value creation system, giving directions to every part or function of the firm. The strategy wheel framework could be applied to the top-level perspective of the strategy or to different strategy perspectives (e.g. financial, customer, internal operations, learning and growth, sustainability, etc.). The strategy wheel framework has been successfully implemented and adapted in different fields. Taylor (1999) developed the six-segment wheel for reviewing and analyzing advertising messages, Cousin (2002) introduced the strategic supply wheel framework to explain the main principles and issues relating to supply management. However, none of the existing research considered the impact of the support functions in the value chain which is also a consideration and addition of this study to the adapted OSW strategy wheel. A fundamental element of applying the strategy wheel framework is to focus on interconnectedness and the associated cause and effect of organizational functions to achieve a strategic purpose. It compels managers and decision makers not to consider any one element in isolation to achieve that purpose. Thus, the strategy wheel can support a systems thinking approach by providing an initial basis to reflect on interdependencies of organizational functional perspectives with the strategic purpose. Systems thinking can be considered a philosophical perspective to describe and understand the causality and interrelationships between factors influencing the behavior of a complex system, for example as an ecological system affected by human-made deforestation (Meadows, 2013; Sterman, 2000). According to the Ellen Macarthur Foundation (2023), systems thinking is the ability to understand how the parts of a system interact to produce the behavior of the whole. Thus, business organizations can be considered complex systems where the performance of interrelated organizational functions affect the overall performance of the organization and the achievement of strategic purposes.

3. Methods

The main approach for this study is a systematic literature review of pertinent literature for developing a theoretical overview of key concepts that are presented, using main databases and journals including Google Scholar, ScienceDirect, JSTOR, Business Source Premier and the University of Bradford Library resources. Data was also collected from both industry and government white papers, publicly available data from government agencies such as the UK Department for Energy and industry analysis from businesses in the OSW sector. Most of the reviewed white papers focused on the UK. The analysis of the literature review was complemented with the current professional activities, tacit knowledge and experience in the energy sector of the main author.

The next step of the study was aimed at adapting and applying the strategy wheel framework to analyze key OSW supply chain areas and functions to support and enhance resilience in supply chain strategies within a CE business environment. The implementation of the strategy wheel framework allowed us to analyze the information collected during the initial stages of the study. This involved grouping key functional areas and operations of the supply chain into broad headers in the strategy wheel framework, considering the related supply chain stage and life cycle phase. Similarly, the strategy wheel framework was also applied to specific supply chain operations/functions (e.g. procurement, manufacturing, logistics, installation, etc.) to achieve a better understanding of the factors influencing SCRes and the level of supply chain circularity. Then an analysis of the supporting tasks required such as technology, human resources and firm infrastructure.

Finally, some recommendations were considered for future research.

4. Applying the Strategy Wheel Framework for a Resilient Supply Chain Strategy

The first step to identify key activities and functional perspectives relevant to support a resilient supply chain strategy was to provide an overview of the OSW supply chain operations. This entailed broad classification according to stages in the supply chain, related project life cycle stages, and tasks and functions performed under each main stage/operation. This model (see Table 1) was initially developed based on the EPCI (Engineering, Procurement, Construction and Installation) model, which is typical in the construction industry. However, it was necessary to enhance the model by considering relevant end of life activities and associated circularity, which is a critical element for this study. Therefore, the supply chain overview model was further expanded to include operation and maintenance activities, and the decommissioning phase.

The next step was to review and analyze the flow of interactions of the OSW supply chain to understand the relationship and how each individual function and component impacts the behavior of the whole. The process of building and analyzing the OSW supply chain highlighted a high level of interconnected reinforcing loops across the different tasks that can benefit from further research using a systems thinking approach. The different tasks were grouped under broad headers based on their stage in the supply chain. Analyzing their relationships and interactions revealed a highly dynamic interaction which were both vertically and horizontal within and across different components of the supply chain. Furthermore, different tasks were serving as input to the next phase suggesting opportunities for further studies on resilience specific to each phase and component of the supply chain. At the end of this stage a graphical representation of components and interactions in Table 2 was created from the data collected.

Once relevant supply chain functions for OSW industry are identified, the most important areas (primary activities) that can enhance the level of resilience of the supply chain are selected. These areas should be carefully considered later in the formulation of more effective supply chain strategies. The strategy wheel framework is constructed around these key functions or areas and their primary activities to ensure that a supply chain strategy can be formulated with an emphasis in resilience (See Figure 1). Thus, the key supply chain functions for the strategy wheel include Sourcing, Procurement, Engineering & Design, Manufacturing, Logistics, Installation, Operation & Maintenance, and Decommissioning. Furthermore, the strategy wheel will also illustrate the consideration that a CE environment will be more relevant in the long-term and this will need to be addressed properly to take full advantage of this opportunity for organizations in the OSW industry. The adapted strategy wheel underscores the importance of supporting activities in the value chain towards improving resilience.

Value chain analysis can be a useful tool in formulating competitive strategies. It enhances understanding the sources of competitive advantage and identify/develop linkages and interrelationships between activities that create Value (Ensign 2001). Porter (1995) value chain framework splits activities of an organization into primary and support activities. Primary activities are those activities that directly contribute to the production of goods or service and its provision to the customer, while supporting activities such as firm's infrastructure, human resources and technology development are those that aid the primary activities but do not directly add value themselves (Stonehouse and Snowdon 2007). The supporting activities such as technology development are represented with a layer in the proposed strategy wheel as they are important and can have an impact on the selected resilience strategy. In fact, industry 4.0 enables SCRes and SC Performance (Qader et al 2022).

Innovation 4.0 (I4.0) comprises the digitalization of the industrial sector through the convergence of physical and virtual worlds and the interconnection of people and things (Hahn 2020). The concept OF I4.0 is described as a scenario where businesses will establish networks that incorporate their machinery, warehousing systems and production facilities in the shape of cyber-physical systems using technologies like the mobile internet, the internet of things and artificial intelligence (Onu, Pradhan and Mbhowa 2023). I4.0 technologies and approaches can improve circularity in the OSW sector through facilitating material recycling systems, real-time tracking and optimization of material flow within the supply chain. The influence of I4.0 in renewable energy production and materials development is significant (Onu, Pradhan and Mbhowa 2023), real time monitoring of production, assessment of equipment, improved communication and visibility of processes are ways that I4.0 supports efficiency and reliability. Data analytics can be used to optimize raw materials and energy use in production and artificial intelligences and associated algorithms can be used to synthesize and design new materials with improved performance characteristics; therefore, technology is an important factor in the development of SCRes strategies (Sunmola and Baryannis 2024),

Table 1. Overview of supply chain activities in the OWS sector.

Supply Chain Activities and Project Life Cycle Stages in the OWS Sector.						
Development	**Engineering & Design**	**Manufacturing**	**Balance of Plant**	**Installation**	**Operations & Maintenance**	**Decommissioning**
Upstream Operations	→	→	→	→	→	**Downstream Operations**
Contract For Difference (government incentive mechanism)	Windfarm Design	Turbines (nacelle, generator, gearbox, rotor, hub, etc.)	AC Substation	Foundations Installation	Planning & Scheduling	End-Of-Life Decommissioning
Final Investment Decision	Topside Design	Blades	DC Substation	Jacket Installation	Maintenance Management (preventive, corrective, predictive)	Fiel Life Extension
Consents	Jacket Design	Monopile (tower)	High Voltage Export Cables	Piling	Asset Management	Seabed Remediation
Permits	Cable Specification	Casting and Forgings	Array Cables	Topside	Resource Management	
Seabed Lease	Surveys	Transition Pieces	Steel Foundations	Wind Turbine Generator Installation	Continuous Improvement	
			Concrete Foundations	Subsea Export Cable Lay		
			Substation Jacket	Array Cable Lay		
				Bathymetry Survey		

Table 2. Interaction Flow of the OSW Supply chain using the EPCID Model

SUPPLY CHAIN OVERVIEW: COMPLEXITY AND INTER-CONNECTEDNESS						
BEGINNING OF LIFE					IN USE	END OF LIFE
SUPPLIER SIDE			MANUFACTURING		END USER / CUSTOMER SIDE	
ENGINEERING	SOURCING	PROCUREMENT	MANUFACTURING	LOGISTICS	PROJECT / END USER	DECOMMISSIONING
CUSTOMER REQUIREMENT	REQUEST FOR SUPPLIER	TECHNICAL BID EVALUATION	RAW MATERIALS	PACKING	INSTALLATION	ENVIRONMENTAL CONDITION
ENGINEERING STUDIES & DESIGN	SUPPLIER EVALUATION	COMMERCIAL BID EVALUATION	MACHINING	TRANSPORTATION	OPERATION	% OF RECYCLABLE MATERIAL
EQUIPMENT / PRODUCT SPEC	SUPPLIER SELECTION	PURCHASE ORDER PLACEMENT	FABRICATION	PRESERVATION	MAINTENANCE	% OF WASTE
INSPECTION & TEST PLANS		CONTRACT MANAGEMENT	ASSEMBLY	STORAGE		RESIDUAL VALUE / REUSE / REPURPOSE
			TESTING	DELIVERY		

The strategy wheel framework can be considered as a practical management tool to allow leadership and management levels in the organization to focus and reflect on the key functions which are necessary to consider and strengthen in order to enhance the level of resilience in supply chain operations and overall performance. This is an important decision-making foundation to later support a more profound strategic analysis, strategy formulation, deployment, monitoring and evaluation. The strategy wheel framework could also help to initiate discussions about specific strategic targets for each identified functional area of the supply chain, including sustainability and CE aspects and considering changes or alternatives for current strategic directions. Thus, early consideration of SMART (Specific, Measurable, Achievable, Relevant and Time-bound) targets is possible for each supply chain function, with emphasis on impact on resilience and CE performance in mind.

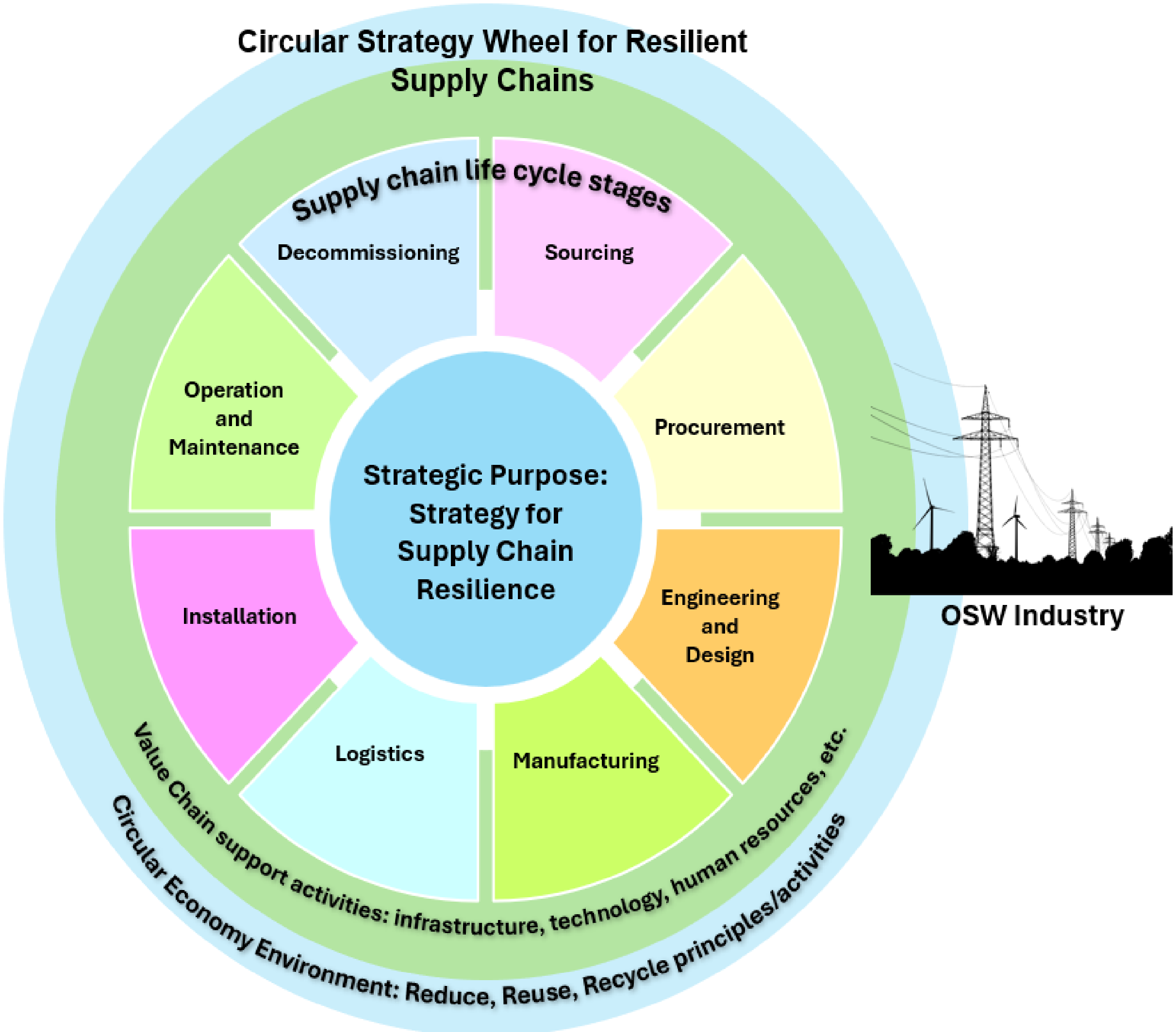

Figure 1. The proposed Circular Strategy Wheel framework.

An analysis and discussion of resilience supply chain strategies applying the strategy wheel confirmed that the effectiveness of a strategy is affected by the life-cycle stage. For example, circularity strategies during the design stage such as lean design and design for deconstruction, may have a different impact during the manufacturing phase or during the decommissioning stage. Therefore, carefully considering the supply chain life-cycle stage during the formulation of supply chain strategies is a very important element of the proposed framework to ensure effective and resilient strategies. A major distinction of the proposed strategy wheel is the inclusion and consideration (at the conception stage) of the value chain support activities which significantly impacts the operationalization of adopted strategies.

Similarly, it is possible to apply the strategy wheel framework to each identified supply chain function (previously identified in the primary strategy wheel) to provide more detailed analysis of the relevant activities and operations to take into account in the formulation of a resilient supply chain, to help linking the strategy to CE opportunities and to define relevant SMART targets (see Figure 2). This model in conjunction with SMART targets will enhance evaluation and measurement of strategy effectiveness as it streamlines adopted strategies, supports evaluation of strategic implementation options within the broad strategy, and identifies relationship and linkages with the supporting tasks. This way, it will also enhance understanding of critical success factors of adopted strategies.

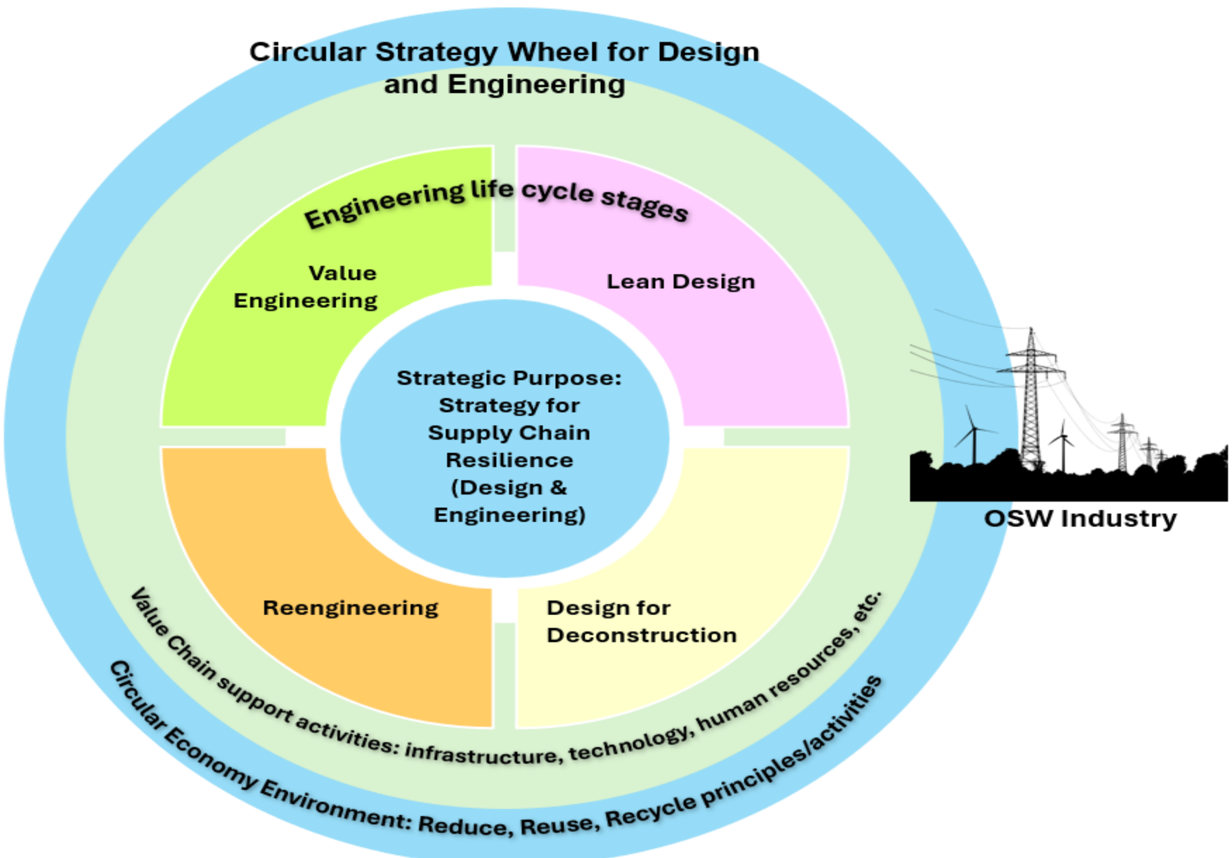

Figure 2. Circular Strategy Wheel framework for the Design & Engineering function to support a resilient OSW supply chain.

The process to apply the strategy wheel framework was repeated for the different supply chain functions of the primary strategy wheel. In this way, relevant opportunities and strategies were defined for the different life cycle stages of the OSW supply chain, with emphasis on circularity (See Table 3). Firstly, identify the main SC tasks, then apply the wheel to a selected specific task and explore opportunities and strategic options for CE introduction to the task. Then a consideration of the supporting activities required to deliver each strategic option and assess this relative to the firm. For example, the lean design option will require expertise in lean principles, value engineering will require sophisticated design software and algorithms and skilled design engineers etc. These will support the firm and industry in selecting strategies that align with its strengths or goals either through collaboration with external partners or in-house designed and engineered solutions. Such CE examples in the industry are where RWE enters agreement with her partners such as Siemens Gamesa Renewable Energy for 40% recyclable blades in her Sofia Offshore Windfarm Project (RWE 2023). RWE Thor monopiles are shielded with reusable covers prior to installation of the turbine towers (OffshoreWindbiz 2025; RWE 2025). Previously, these covers were disposed of after use, but this innovative design between RWE and a Dutch company circular covers have given a new lease of life to the covers as they will be reused on other projects. A framework like the proposed strategy wheel will enhance the development of specific strategies as it would aid clarifying the essential support activities required and support supplier evaluation with regards attributes and output required from a supplier to complement the firm towards realizing a particular strategy.

5. Findings and Recommendations

5.1 Key Findings

The paper highlights the need for emphasizing supply chain resilience during the early stages of strategy analysis and formulation in the context of OSW industry. Furthermore, CE principles should be also considered in the definition of key strategic goals and in the formulation of effective resilience strategies to enhance supply chain long-term performance. The paper emphasizes the importance of supporting activities in the execution of selected strategies

The paper emphasizes that there is no single encompassing strategy for circularity across the entire OSW supply chain. Although, it finds that there are elements of circularity that can be applied to every stage/operation of the supply chain such as the concepts of reduce, reuse and recycle, these can be complemented with other strategies for specific supply chain activities and at specific life cycle stage to further increase the level of circularity.

The study also stresses that strategies for supply chain resilience can be categorized under three main groups. Firstly, there are strategies that can be applied in every aspect of the supply chain such as the concepts of Reduce, Reuse and Recycle. The second category consists of strategies that are applied to specific phases or functional areas of the supply chain such as lean manufacturing and modular outfitting for manufacturing components, and Circular Business models and considerations for residual value at the end of life when developing the projects. The third category includes strategies beyond organization. These are strategies that can be applied at an industry or regional level such as the formation of clusters and collaborative utilization of assets to minimize energy consumption or increased production of assets which take up resources. Collaboration can be an important factor to achieve strategic resilience in supply chains (Singh et al., 2023).

Table 3. Opportunities and strategies for introducing circularity along the OSW supply chain.

OFFSHORE WIND SECTOR - OPPORTUNITIES & STRATEGIES FOR CIRCULARITY ALONG THE SUPPLY CHAIN						
REDUCE / REUSE / RECYCLE						
DEVELOPMENT	ENGINEERING & DESIGN	COMPONENTS	BALANCE OF PLANT	INSTALLATION	O & M	DECOMMISSIONING
CIRCULAR BUSINESS MODEL	DESIGN FOR DECONSTRUCTION	MODULAR OUTFITTING	WASTE MANAGEMENT PLANNING	REPURPOSE FACILITIES	LESS HOLDING INVENTORY	BETTER EXTRACTION TECH
RESIDUAL VALUE MODEL	LEAN DESIGN	JUST-IN-TIME	LEAN CONSTRUCTION	REUSE MATERIALS	ENERGY EFFICIENCY	REFURBISHMENT
	VALUE ENGINEERING	LEAN MANUFACTURING		SEGMENTAL LOGISTICS		
CLUSTERS / STANDARDISATION / FLEXIBLE-LOGISTICS / SHARED ASSETS / COLLABORATIVE CONSUMPTION / REGULATION						

The study finds that the number of different operations and activities along the supply chain could have an impact on the sustainability and circularity maturity level of the entire supply chain. Furthermore, regulations are an important factor in converging the different supply chain players towards reaching certain levels of sustainability, as profitability and budget constraints are major factors of consideration when businesses and projects are selecting circularity and overall sustainability strategies. For example, with regards to maintenance strategy for wind turbines, research like Zied et al. (2022), proposes a sequential resolution approach which allows to determine an optimal production and imperfect maintenance plan. Such approaches select an adequate number of components to be maintained for each period with an intent to minimize total maintenance cost while ensuring minimum reliability levels for the next energy production period (Zied et al. 2023). Therefore, ensure that wind turbines are systematically maintained not only a cost-effective manner but also in a manner that increases reliability, minimizes risk of failure and need for replacement maintenance which improves circularity.

5.2 Recommendations for Future Work

The study recommends the introduction of SMART (Specific, Measurable, Achievable, Relevant and Time-bound) framework when defining and setting targets for strategy implementation. Furthermore, it would recommend further studies on what attributes constitute supply chain resilience in the context of a circular economy.

It is also recommended that organizations integrating the supply chain of the OSW industry consider introducing circularity at the very early stages of strategy formulation and supply chain development, and not as a remedial action to respond to uncertainty in the business environment, as key opportunities could be missed and implementation costs would be higher. It recommends linking circularity and supply chain resilience to the overall business strategy and business model for improved effectiveness.

The future work regarding this study considers the development of a systematic methodology to analyze, formulate and deploy more effective strategies to strengthen long-term resilience in the supply chains of the OSW industry. The process of generating effective strategies is not a simple decision-making task and it is important to consider the organizational structure, internal and external capabilities and resources at different organizational levels and functions (Munive-Hernandez et al, 2004). An explicit and systematic approach can help to ensure consistency in strategy generation and enhance communicating the strategy throughout the organization. The following proposed methodology needs further analysis and refinement. An initial approach considers the following stages in the development, revision and selection of resilience strategies for the OSW supply chain within a CE environment:

- Model key operations/activities of the supply chain.
- Assign Life-Cycle stages to relevant supply chain operations.
- Apply the strategy wheel framework to the supply chain strategy perspective, including specific supply chain operations/stages.
- Define SMART targets.
- Select supply chain strategies to achieve long-term targets.
- Monitor and evaluate strategy performance over time relative to set targets.

Furthermore, a systems thinking and systems dynamics approaches can be combined to further analyze, model and simulate the dynamic behavior of a resilient supply chain within a CE environment. A systems thinking approach would allow to build and apply Causal Loop Diagrams to further analyze key factors influencing the level of resilience in the performance of a supply chain. In addition, this tool would also facilitate understanding the nature of the causal interrelationships among such factors, helping also to understand the structure of such a complex system (e.g. supply chain strategies), as shown in Figure 3. Supply Chain Resilience could be supported and enhanced through a strategic feedback loop integrated by an effective strategy process (analysis, formulation, implementation and control), which could respond promptly to internal and external disruptive events. Systems thinking can be applied to help understanding different aspects of operations as a complex system, from strategic to operational perspectives (Sterman, 2000, AlMashaqbeh, S. and Munive-Hernandez, 2023, Gahigiro et al., 2023).

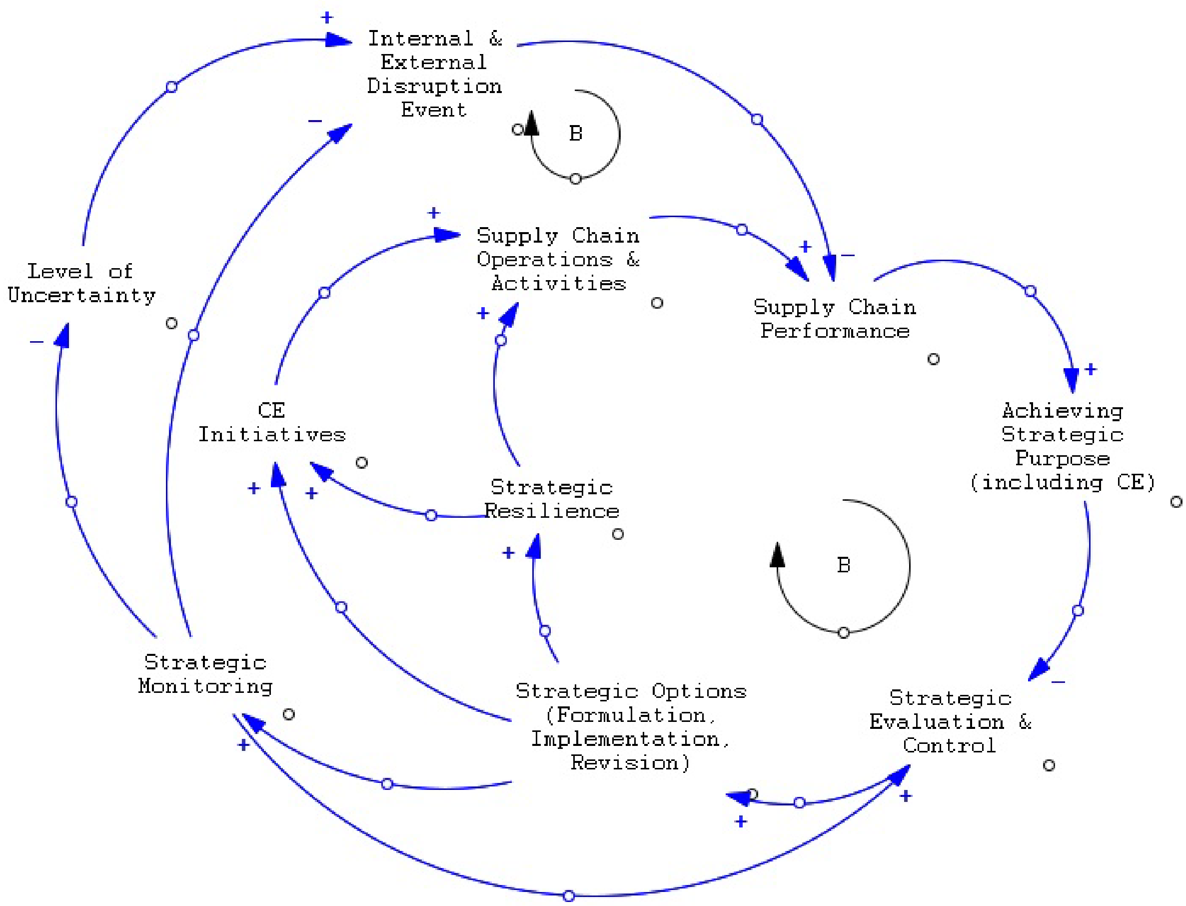

Figure 3. A Systems Thinking approach can help to analyze further key causal relationships and feedback loops influencing Strategic Supply Chain Resilience.

In the context of understanding complex systems, it is also important to try to quantify a Causal Loop Diagram (model) by "translating" it into a System Dynamics model. This would allow to quantify the effect of different variables (supply chain factors) and experiment with different scenarios through computer simulations (to test resilience in supply chains). Thus, it is possible to achieve a better understanding of the dynamic behavior of a complex system with a more strategic perspective (long-term performance) (AlMashaqbeh et al., 2021).

6. Conclusion

This paper finds that there is no single all-encompassing circular strategy for improving supply chain resilience across the entire OSW Supply chain. Instead, it identifies various strategies that can be better suited to provide desired results when tailored to specific components of the supply chain. In addition, the efficacy of the strategies has a direct relationship with the time of introducing the circularity strategy and the targeted phases and components of the supply chain at that point in time. The earlier circularity is introduced into the SC, the better and greater impact it is likely to have. In conclusion, circularity should be considered from the concept and development stage and should be aligned with the overall business strategy and model to increase impact on improving sustainability and supply chain resilience. The paper highlights the importance of supporting activities in the value chain such as technology and hypothesizes that they will have an impact in the success or failure of the selected strategy. Finally, this paper expands the conventional strategy wheel to include the value chain support activities during strategy formulation and implementation. Offering an opportunity to evaluate the requirements and suitability of the organization to execute its selected strategy, ensuring they have the right infrastructure, human resources, skillset and technology for their selected strategy.

In conclusion, this study identifies the key stages of the OSW SC within a circular economy environment to include development, engineering and design, manufacturing, balance of plant, installation, operation and maintenance, and decommissioning. It proposes the expanded strategy wheel for integration of CE principles into the OSW SC to increase resilience as it improves strategy formulation and execution as it allows for early consideration of the firms attributes in the form of support activities in the value chain at the strategy conception stage which increases its effectiveness and chances of success.

References

ALMashaqbeh, S., Munive-Hernandez, J., Khan, M., Analysing the Impact of Supply Chain Risks on the Strategic Performance of Power Generation Companies: a System Dynamics Approach, International Journal of Business Performance and Supply Chain Modelling, vol. 12, no. 4, Inderscience, 2021. DOI: 10.1504/IJBPSCM.2021.10044851

AlMashaqbeh, S. and Munive-Hernandez, J., Risk Analysis under a Circular Economy Context Using a Systems Thinking Approach, *Sustainability*, vol. 15, no. 5, 4141, 2023. https://doi.org/10.3390/su15054141

Behzadi, G., O'Sullivan, M. J., and Olsen, T., On metrics for supply chain resilience, *European Journal of Operational Research,* vol. 287, no. 1, pp145 – 158, 2020.

Cousins, P., Lamming, R., Lawson, B. and Squire, B., *Strategic Supply Management: Principles, Theories and Practice*, 1st Edition, Prentice Hall, 2008.

Dutta, D. K. and Hora, M, From invention success to commercialization success: technology ventures and the benefits of upstream and downstream supply-chain alliances, *Journal of Small Business Management*, vol. 55, pp. 216-235, 2017.

Ellen MacArthur Foundation (a), Towards a Circular Economy: Business Rationale for an Accelerated Transition, Ellen MacArthur Foundation, 2015 a.

Ellen MacArthur Foundation (b), Growth Within: A Circular Economy Vision for a Competitive Europe, Ellen MacArthur Foundation, 2015 b.

Ensign, P. C., Value chain analysis and competitive advantage, *Journal of General Management,* vol. 27, no. 1, Pp. 18 – 42, 2001.

European Parliament, Circular economy: definition, importance and benefits. *Topics, online:* https://www.europarl.europa.eu/topics/en/article/20151201STO05603/circular-economy-definition-importance-and-benefits, 2023.

Gahigiro, M., Munive-Hernandez, J.E, ALMashaqbeh, S., A Systems Thinking approach to analyse sustainability strategies, employee motivation and impact on financial performance, *Proceedings of the 7th European Conference on Industrial Engineering and Operations Management*, IEOM Society International, Augsburg, Germany, 2024. https://doi.org/10.46254/EU07.20240128

Hahn, G. J., Industry 4.0: a supply chain innovation perspective, *International journal of production research*, vol. 58, no. 5, pp. 1425 – 1441, 2020.

Ivanov, D., Structural dynamics and resilience in supply Chain risk management, *International Series in Operations Research and Management,* 2018.

Korhonen, J., Honkasalo, A. and Seppala, J., Circular Economy: The Concepts and its Limitations, *Ecological Economics,* vol. 143, no. 1. Pp. 37 – 48, 2017

Ma, H., Shi, H., and Liao, M., circular economy and new research directions in Sustainability. *International Series in Operations and Management Science,* vol. 310, no. 1, pp. 141 – 168, 2021.

Meadows, D., Thinking in systems: a primer, Sustainability Institute, White River Junction, Chelsea Green, 2013.

Montgomery, C., The Strategist: be the leader your business needs, Collins, 2012.

Morash, E. A., Supply Chain Strategies, Capabilities, and Performance, Transportation Journal, vol. 41, no. 1, pp. 37 – 54, 2001

Morrissey, J., Heldkamp, C. P., 2022, *Demanding Sustainability: pillars to (re)build shared prosperity*. Palmgrave, MacMilian.

Munive-Hernandez, J.E., Dewhurst, F.W., Pritchard, M.C., Barber, K.D., Modelling the Strategy Management Process: an initial BPM approach, *Business Process Management Journal*, vol. 10, no. 6, pp. 691-711, 2004. https://doi.org/10.1108/14637150410567884

Olivieira, A. and Rangel, L., Challenges and opportunities in a circular economy for a local productive arrangement of furniture in Brazil, *Resource, Conservation and Recycling,* vol. 135, no. 1, PP. 202 – 209, 2018.

Pani, A., Shirkole, S. and Mujumdar, A., Importance of renewable energy in the fight against climate change, *Drying Technology,* vol. 40, no. 13, pp. 2581 – 2582, 2022.

Pellicelli, M., *The Digital Transformation Supply Chain,* Elsevier, 2022.

Pienaar, W., *Introduction to Business Logistics,* Oxford University, South Africa, 2009.

Porter, M. E., *Competitive advantage: creating and sustaining superior performance,* the free press, New York, 1985.

Singh, J., Hamid, A. and Garza-Reyes, J., Supply chain resilience strategies and their impact on sustainability: an investigation from the automobile sector, *Supply Chain Management*, vol. 28, no. 4, pp. 787-802, 2023. https://doi.org/10.1108/SCM-06-2022-0225

RWE, RWE's sofia offshore windfarm to use recyclable blades. Online: https://www.rwe.com/en/press/rwe-offshore-wind-gmbh/2023-03-09-rwes-sofia-offshore-wind-farm-to-use-recyclable-blades/, 2023.

RWE, Circular economy: RWE gives monopile foundation covers a new lease of life. Online: https://thor.rwe.com/press-and-news/2025-02-14-circular-economy-rwe-gives-monopile-foundation-covers-a-new-lease-of-life, 2025.

Sassanelli, C., Rosa, P., Rocca, R. and Terzi, S., Circular Economy Performance assessment methods; A systematic literature review, *Journal of cleaner production*, vol. 229, pp 440-453, 2019. https://doi.org/10.1016/j.jclepro.2019.05.019.

Sterman, J., Business Dynamics: Systems Thinking and Modeling for a Complex World, Irwin McGraw-Hill, 2000.

Stonehouse, G. and Snowdon, B., Competitive advantage revisited: Michael Porter on strategy and competitiveness, *Journal of management inquiry,* vol. 16, no. 3, pp. 256 – 273, 2007.

Sunmola, F. and Baryannis, G., *Artificial intelligence opportunities for resilient supply chains,* IFAC Conference paper, vol. 58, pp. 813 – 818, 2024.

Taylor, R. E., A six segment message strategy wheel, Journal of Advertising Research, vol. 39, no. 6, pp 7 – 17, 1999.

UNEP, *Emissions gap report,* United Nations Environment Program, 2024.

Velenturf, A., Challenges and Opportunities for sustainable offshore wind development, preliminary findings from a literature review and expert survey, *SRI Papers*, Sustainability Research Institute (SRI), School of Earth and Environment, The University of Leeds, no. 122, 2020. Available online: https://sri-working-papers.leeds.ac.uk/wp-content/uploads/sites/67/2020/11/SRIPs-122.pdf.

Wu, L., Yue, X. and Jin. A., Smart supply chain management: review and implications for future research, *International Journal of Logistics Management,* vol, 27, pp 395 – 417, 2016.

Zied, H., Nidal, R., Mohammed, A. K., Maryem, B., Improved maintenance strategy for the wund turbine system under operating and climatic conditions, *Proceedings of the Institution of Mechanical Engineers, Part o: Journal of Risk and Reliability,* vol. 2, pp. 349 – 365, 2022.

Zied, H., Nidal, R., Mohammed, A. K., Maryem, B., An optimal combined production and maintenance policies for a wind farm with environmental and operational considerations, *Non-destructive testing and condition monitoring techniques in wind energy,* pp. 133 – 175, 2023.

Biographies

Emeka J. Nwonu is an industry professional with over 15 years' experience of delivering projects in the energy sector and the last 5 years planning, monitoring and controlling the delivery of HVDC and Offshore wind energy projects. He is experienced in Offshore Converter Topside Fabrication, Offshore Transport and Installation, Onshore converter stations building and balance of Plant and HVDC. He is currently a post graduate research student at the University of Bradford researching strategies for supply chain resilience within a circular economy environment. He is a lean 6 Sigma Yellow and Green Belt practitioner, and his research interests include Circular economy, sustainability and sustainable strategies, Operations Improvement strategies, Supply Chain resilience Strategies, Systems thinking and Systems dynamics.

Jose Eduardo Munive-Hernandez is an associate professor in Advanced Manufacturing Engineering, Faculty of Engineering and Digital Technologies, University of Bradford. He received his PhD in Total Technology from the University of Manchester Institute of Science and Technology in 2003. He has Industrial experience in the manufacturing sector and in the automotive industry. His research interests include process improvement in operations and supply chains, analysis and modelling organizational systems, systems thinking and systems dynamics, performance measurement, strategic measurement, and sustainable circular economy.

Cuong Dao is an associate professor in sustainable energy systems, Faculty of Engineering and Digital Technologies, University of Bradford.