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A Methodological Framework for Analysis and Theorization of Circular Supply Chain at the System Context Level

Shiva Abdoli[1], Sijia Xie[1] , Bahador Bahramimianrood[1], Mohammed Malaibari[1], Thomas Stringer[2]

[1]*School of Mechanical and Manufacuring Engineerng, Univerity of New South Wales, Sydney, Asustralia*
[2]*Department of Industrial Engineering, Tecnológico de Monterrey, Monterrey, Mexico*

Abstract

Circular Economy concept (CE) revolves aims enhancing resource efficiency through product lifecycle in technical or biological cycles. The former aims to enhance resource efficiency through waste reduction, recycling, reuse, reducing material consumption, and so on. While in the latter, biodegradable materials are returned to earth through processes like composting. There is a lack of comprehensive theorization of CE concept, when focus is supply chain management/value regeneration at technical cycle. Such a lack and consequently a generic understanding can hinder realizing the full potential of CE. This research aims to propose a theorization of CE in the technical cycle through a supply chain management lens. To this end, the systems engineering approach and life cycle assessment (LCA) are integrated to analyse and theorize the circular supply chain/value regeneration. This paper proposed the novel perspective of supply chain as a system of systems (SoS), which allows identifying the enablers, players, and interactions that influence the realization of CE by implementing its known R-strategies. This paper suggested modification of the existing functional unit definition in LCA method such that the proposed definition takes into account the dynamic/evolving boundary of a supply chain when integrating the R-strategies. Moreover, this paper proposed the 'CE system context' for the supply chain SoS. The proposed structured approach allows the development of the Supply chain SoS within its CE context (Supply Chain SoS-CE context). Certain measures are introduced to assess the effectiveness of integrating R-strategies assuring they contribute to CE realization while network theory concepts are used to assess the criticality of various players in Supply Chain SoS-CE context. A roadmap for development of 'Supply Chain SoS-CE context' is introduced in the light of Industry 4.0.

Keywords

Circular Economy; Supply Chain; System Context; Systems Engineering

1. Introduction

Sustainable development seeks to reduce the Environmental Impact (EI) associated with product development. With the increase in population/demand, concerns of massive resource usage, depletion, and scarcity have risen, making material efficiency in product development a top priority. Broadly, efficiency means minimizing consumption of resources while achieving the same output. In product development context, material efficiency means producing same functional output by consuming less material in value creation process, known as supply chain [1] . This can contribute to reducing EI, such as waste generation. This idea has led to emergence of Circular Economy (CE), aiming at minimization of waste generation and resource consumption throughout life cycle of services and products while still meeting socioeconomic

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development goals [2, 3]. Various pathways have been suggested and explored in realization of CE [4], such as enhancing material recycling when product reached its End of Life (EoL) instead of landfilling or extending its lifecycle by different means, such as reusing product or some of its components. CE can strongly support Goal 12 of sustainable development goals (responsible production and consumption), for which Target 12.5 is about substantial waste reduction, through prevention, reduction, recycling, and reuse – which are the core aspects of CE [5]. Achieving this target requires accommodation of extra activities in supply chain, known as reverse logistics, such as product collection and value recovery. A supply chain that includes such activities is called a closed loop supply chain opposed to a linear one [6]. However, Supply Chain Management (SCM) – whether for linear or closed loop – is complex in today's business climate. SCM involves coordination of a diverse activities, from sourcing of input materials to production process, inventory management, and distribution of finished goods to consumers [6]. Due to this large-scale, multidisciplinary, and dynamic nature of involved activities in supply chains, they can be considered complex systems from system theory perspective [7]. Including reverse logistic activities in a supply chain can make SCM even more complex by adding extra activities while aiming to satisfy CE plus a firm's business objectives. This complexity and consequently poor large-scale data management is a substantial hurdle for CE progress and can be a reason why CE and its reverse logistics channel have not been explored/implemented in many supply chains [8]. Therefore, there is a need to utilize methods that allow achieving a proper understating of the complex structure of supply chains when including the reverse logistic activities. Researchers from different domains have investigated CE within their own discipline-specific aspects and as a result, there are various definitions for CE, classification of its activities, and their relationships [9-11]. Such diversity with a lack of comprehensive mapping and classification can lead to confusion and inhibiting realization of CE's full potential, especially when the focus is on a reverse SCM. System thinking is referred as the art of simplifying complexity by seeing through chaos, managing interdependency, and understanding choices [12]. Systems engineering is a well-known approaches in applying such an art, especially in engineering domains [10, 13]. Systems engineering can contribute to identifying the overlooked concepts that can benefit CE in a general sense by cross-examination of concepts that are only investigated in a specific domain with a narrow focus. In the report published by Ellen MacArthur Foundation, the importance of system thinking for CE realization is highlighted [4]: "*System thinking emphasises flow and connection over time and has the potential to encompass regenerative conditions rather than needing to limit its focus to one or more parts and the short term.*" This paper aims to utilize systems engineering approach for theorization of supply chain from CE perspective. This novel theorization promotes understanding of concepts, their relationship, and their roles in big picture of CE. Moreover, perspective offered in this research allows identifying challenges and limitations to realize CE in SCM domain and offering a road map for SCM to realize CE.

2. State of the Literature

CE has gained considerable interest recently [14] seeking to transit from conventional linear 'take-make-dispose' approach to a more sustainable/economically viable system. The value of a linear system is derived from maximisation of production and sales. The circular system emphasizes on continuous optimisation of value of products, components, and materials by ensuring their highest utility is maintained throughout their lifecycle [15]. Yet, the shift from a conventional to a Circular Supply Chain (CSC) entails numerous obstacles. De Angelis et al. emphasise the importance of fostering more collaboration, not only within immediate confines of industry, beyond its conventional boundaries [14].

Ada et al. classified several obstacles for implementation of CE [16] including business-related concerns, financial limitations, technological setbacks, management complexities, and SCM difficulties. Notwithstanding these significant obstacles, the authors posit that harnessing Industry 4.0 technologies, encompassing IoT, cloud-based technologies, machine learning, and blockchain, can serve as a viable remedy for surmounting these challenges.

There is consensus in the literature that there is a lack of a comprehensive framework for integration of CE within the realm of SCM [9-11]. For example, this reference [17] emphasised the significance of aligning product design with SCM decisions to effectively transition towards CE. The authors suggest that adopting a comprehensive approach has the potential to generate improved outcomes in terms of EI, society, and economy. Therefore, this research does not review the available literature on CE that have narrower and refers the interested readers for detail concepts to the existing literature.

3. Concepts and Methods

In system theory, a system is a set of interacting elements serving a purpose that cannot be achieved by individuals, as its emerging behaviour [18]. An ‘open’ system interacts with its environment. In systems engineering, System of Interest (SoI) operates in a wider system interacting with other systems. The system environment consists of open systems that can influence SoI. System ‘Context’ contains the environment. Boundary of a system defines its elements and their interaction with environment. SoS is a system whose elements are independent systems, called Constituent Systems (CSs). A system is considered socio-technical when it interacts with social aspects of environment and its behaviour is determined by technical elements and their interaction with social systems [13, 19]. In systems engineering, system architecture is a key artefact demonstrating overall topology of a system, its function, its elements, and their relationships. This paper proposes an approach for modelling the system context which contains a closed loop supply chain. Modelling a context can be done through observation and classification of elements with an abstract conceptualisation. To this end, in next section first the technical concepts of CE and supply chain are investigated, then they are integrated to develop the supply chain system of context from CE perspective to propose a theorization of supply chain-CE.

3.1 Technical Concepts

3.1.1 Circular Economy Cycles and R-Strategies

In CE domain, two types of nutrients are recognized: biological and technical [20]. Biological nutrients are organic materials that can be returned to environment where they biodegrade and contribute to natural cycles following natural ecosystems’ principles (after product used in its life cycle). Technical nutrients are inorganic in the form of materials and components that can be reused in different ways within industrial systems, thus preserving the energy, labour, and resources went into their production. Technical nutrients are synthetics and CE aims to use them within closed-loop industrial cycles. An example is a modular smartphone, in which some components can be upgraded, repaired, or recycled. This keeps the technical nutrients within the product cycle and out of the waste stream for as long as possible. This paper focuses on technical cycles to manage the study scale and including the biological cycle will be investigated in future works.

CE revolves around a set of strategies, referred to R-strategies, as used to optimize lifecycle of products and materials. They range from original 3R approach - Reduce, Reuse, Recycle- to more comprehensive 9R frameworks [11, 21]. Each R-strategy offers a different level of circularity, resource efficiency, and EI mitigation; hence, their selection and implementation involve different stakeholders, technologies, and social aspects. The first six R-strategies explained below sit within this paper’s scope.

- Repair: fixing a damaged product to extend its useful life.
- Refurbish: restoring a used product close to its original condition to extend its lifecycle and reducing waste, for example refurbishing older laptops for resale or donation.

- Reuse: For biological nutrients, this might involve creating compost from organic waste. With technical nutrients, this could entail reusing components from old devices in new ones.
- Remanufacture: dismantling a product, repairing, or replacing damaged parts then reassembling it to improve its performance or efficiency, such as rebuilding a car engine to extend its life.
- Recycle: converting waste materials into new materials, reducing raw material extraction, and conserving resources. An example of biological nutrients can be recycling plant-based packaging into new products, while for technical nutrients, melting down and reforming metal components from discarded electronics fits this strategy.
- Recover: obtaining value from waste. In biological nutrients, this could mean composting organic waste. For technical nutrients, it could involve energy recovery, such as incinerating non-recyclable plastics to generate heat or electricity.
- Reduce: In biological nutrients, this could involve minimizing packaging in a product. For technical nutrients, it may mean designing products for energy efficiency.
- Rethink: reevaluating the need for a product or service, potentially shifting consumption habits to more sustainable options.
- Refuse: actively choosing not to use or buy unsustainable products or services.

3.1.2 Reverse Supply Chain

Efficacy and efficiency of SCM system are contingent upon a seamless integration between logistical and cross-functional drivers that underpin supply chain performance, including facilities, inventory management, transportation, production planning, information systems, and sourcing strategies [22]. SCM approaches have undergone significant advancements for enhancing efficiency/effectiveness. These include Lean Manufacturing approach, focusing on waste reduction in manufacturing process and Enterprise Resource Planning (ERP) as a tool to facilitate integration of diverse SCM functions. Transition from a linear supply chain to a CSC can be achieved through implementation of three strategies: narrowing, slowing, and closing [23]. Narrowing strategy entails deliberate reduction of material/energy consumption within production process. In inventory management, CE ideology promotes adoption of practices that prioritize reuse/recycling of products. This approach holds potential to curtail demand for raw materials and mitigate waste generation. The initial phase in transition from a conventional supply chain to a CE is implementation of a narrowing strategy. The process of slowing resource loops encompasses implementation of various strategies, including repair, remanufacturing, and reuse to prolong products' lifecycle. The reverse supply chain assumes a pivotal position, encompassing a series of activities aimed at redirecting goods from their customary end-point to extract value or ensure appropriate disposal, as explained by remanufacturing, repair, and refurbishing [24].

3.2 Theorization of 'Supply Chain-Circular Economy' System of Systems Context

CE has a cyclic perspective while traditional forward/open SCM view has a sequential one [14]. The scale of involving players in a CE can be broad and dynamic which must be addressed when analysing integration of R-strategies with SCM. This paper orchestrates various methods/approaches to address the gap between linear and circular perspective while acknowledging the dynamic and evolving nature of CE. To this end, the systems engineering principle, particularly concepts of SoS and system context are used. Moreover, Life Cycle Assessment (LCA) method is used to assist in system boundary definition and providing a foundation for EI calculation. This helps to identify the best R-strategy or set of R-strategies in achieving CE objectives or reducing the total EI at higher supply chain SoS-CE context level. The proposed approach is demonstrated in Figure 1 and is explained below.

3.2.1 Supply Chain System of Systems

CSs in an SoS are networked to achieve a higher capability that may not be achieved with individual CSs that have their own stakeholders. SoSs are evolved by adding new or removing existing CSs in their lifetime to adapt to their environment. This paper proposes modelling a supply chain in CE context (from reverse supply chain perspective) as an SoS which includes various systems such as original manufacturer, assembly, and logistics systems. This perspective allows integration of R-Strategies with supply chain, which may require including new technological and social systems such as, recycling, re-manufacturing, and colleting systems. While all systems within both original and possible closed loop supply chain can function independently and have their own objectives, their integration allows achieving the supply chain and CE objectives. Such integration can happen or change over time, the proposing perspective (supply chain as an SoS) allows adapting to this evolving aspect of supply chains in CE context by including new systems or adapting the existing ones when its needed. This is referred to loosed coupling from the systems engineering perspective.

3.2.2 Supply Chain-SoS Boundary Definition and LCA

The boundary of a system defines its elements and their interaction with environment [13]. In adapting supply chains with CE concept, this paper defines the supply chain as the SoI (Supply chain System of Systems interest: Supply chain SoSoI) that delivers a product or service to customer. However, dynamic adaption of supply chain to integrate R-strategies dynamically evolve its system boundary. Yet, it is needed to have a measuring unit and a basis for comparison and to assess effectiveness of integration of any R-strategies in realization of CE objectives. Therefore, this research integrates LCA method in its proposed approach. In LCA, functional unit specifies the quantity of a product/service to be delivered to an end user. System boundary in LCA defines the processes that must be included in analysis to calculate EI associated with delivering the functional unit. To define the supply chain boundary, this research separates use cases that are internal to supply chain of a product/service from actors that are external to supply chain. Such systems belong to the context of the supply chain as shown in Figure 1.

For ease of reference, this paper calls the functional unit defined for a product/service without any CE strategy as forward functional unit, $Functional\ Value\ unit_{Forward}$. This is used to define the boundary for forward-supply chain. The integration of various R-Strategies from the planning stage or through the lifecycle of product/service might change that initial boundary. This research suggests adjusting the initial functional unit when integrating R-strategies. This helps to assess the efficacy of integration of R-Strategies and find the proper set of R-strategies. Accordingly, the EI associated with $Functional\ Value\ unit_{Forward}$ can be calculated using LCA. For example, the $Functional\ Value\ unit_{Forward}$ can be defined as10 years of car driving and landfill later, which its associated carbon footprint can be calculated using LCA. Then, remanufacturing of certain components can be analysed by defining a new functional unit, $Functional\ Value\ unit_{R-strategy}$, as delivering re-manufactured components to be used in a new car. This strategy requires integration of re-manufacturing facilities and collecting systems. As a result, EI associated with new functional unit, which are respectively called EI_{CE} and $Functional\ Value\ unit_{CE}$, should be updated as shown in (1) and (2). The environmental efficacy of R-strategy can be calculated as the ratio of EI_{CE} to the $Functional\ Value\ unit_{CE}$. However, this research proposed to modify the way that a functional unit is generally presented by demonstrating it as a value generation within economy. This allows comparing the ratios in Equations (3) and (4). Hence, traditional functional unit is called the functional value unit in this paper. For example, generating value of 10 years of car driving can be measured within the economy. Likewise, generating value of 10 years of car driving while certain components are re-manufactured to be used in the new car is a new functional value unit measured in the economy. This can be formulated as the ratio of economic value of generated function within current size of the economy. Another alternative would be to calculate the ratio of the addressed demand by generated function to the total demand within the economy. Both alternatives offer a ratio for the generated functional value unit. Integration of proposed approach with known Input-Output analysis in CE domain can be beneficial in this proposed framework which is part of the future research of current work. Either of these alternatives suggests extracting value from a product's life cycle and implying that products are containers of value that can be successively unlocked as they circulate through various R-strategies.

$$Functional\ Value\ unit_{CE} = Functional\ Value\ unit_{Forward} + Functional\ Value\ unit_{R-strategy} \tag{1}$$

$$\mathrm{EI}_{\mathrm{CE}} = \mathrm{EI}_{\mathrm{Forward}} + \mathrm{EI}_{\mathrm{R-strategy}} \tag{2}$$

$$\text{R-strategy-Efficiency} = \mathrm{EI}_{\mathrm{CE}} / \text{Functional Value unit}_{\mathrm{CE}} \tag{3}$$

$$\text{Forward-SCM Efficiency} = \mathrm{EI}_{\mathrm{Forward}} / \text{Functional Value unit}_{\mathrm{Forward}} \tag{4}$$

From systems engineering perspective, the proposed approach allows to analyse effectiveness of each R-strategy from economic, performance, and CE objectives perspectives. When the product/service approaches its EoL in any of demonstrated cycles in Figure 1, the above measures can be calculated to identify the best set of future R-strategies. Because, depending on the value proposition, it might not be beneficial economically/environmentally to conduct some intermediate strategies and instead directly move to recycling. This depends on the level of upfront resource consumption of the components. Thus, an agreement can be made between stakeholders and developers in any of those lifecycles and future ones to implement a specific R-strategy with an agreed condition offering the chance of delivering an extra value for which they are willing to invest specific cost and other resources.

3.2.3 Supply Chain- Circular Economy System Context

A System context is a set of system interrelationships associated with a particular system of interest (SoI) within a real-world environment [13]. Generally, system context can be very helpful to get a better understanding of a problem and developing solutions which require a proper combination of social and technological enablers. These are called as socio-technical system contexts, which as explained implementation of R-strategies require both social and technological enablers and CE context fits well to socio-technical system context definition. Closing loops in supply chain from CE perspective, requires investments in recalibrating relationships with enablers of forward and backward supply chain.

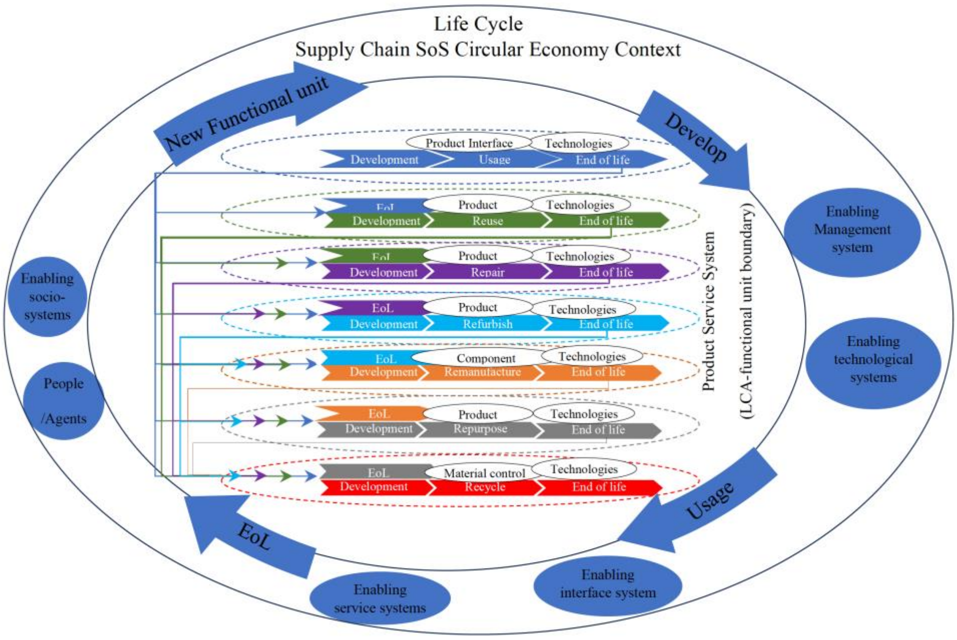

Figure 1: Supply chain SoS Circular Economy context

This paper proposes a novel perspective of looking at supply chain as SoI and an SoS that operates within its context. Integration of R-strategies in a Supply Chain SoS of Interest (SoSoI) impacts its context, meaning SoSoI not only might have an evolving and broader boundary but also a broader and evolving context too. This is called Supply Chain Circular Economy System of Systems Context in this paper: SC-CE-Context. The advantage of proposed view in this paper (developing SC-CE Context) would be allowing to focus on supply chain as SoI but not lose sight of its all-holistic relationships, interactions, and influences beyond boundary of supply chain itself, which implementation of CE view (R-strategies) require many relations/interactions. This approach allows identifying enabling systems and their activities focused on creation and re-creation of value promoting a holistic approach over a lifecycle. Based on systems engineering principles, this research suggests a novel procedure to understand supply chain SoSoI and its CE context. This allows capturing important relationships between its elements, the systems with which it works directly, and any other systems with which it might interact in its context. This approach combines various views to ensure capturing all the important elements, relationships, and interactions that are needed when applying the CE at the supply chain.

- Product/service system view
  - Define the lifecycle of the product/service system developed in the supply chain of interest.
  - Identify its needed technological and social enablers (systems) during its lifecycle.
- Forward view: open loop supply chain system and its context
  - Define the boundary of the forward supply chain system.
  - Define the elements within the forward supply chain.
  - Define external elements which interact across the boundary of a forward supply chain SoI
  - Identify enabling systems (following ISO 15288[25]): systems (or services) utilized at various stages in life (cycle, e.g., utilization) to facilitate the SoI in achieving its objectives.
- Cyclic view: Closed-loop supply chain system of interest and its context.
  - Define the R-strategies.
  - Define the enabling systems/services for each R-strategy.
  - Define the interactions/relationships between the supply chain elements and identified enabling systems/services for R-strategies.
- Integration:
  - Identify the possible overlap between the identified enabling systems/services.
  - Define the importance of enabling systems/services and supply chain systems elements based on the network theory measures (explained below)

The proposed approach started with product/service system view, because the product/service system within a supply chain is first focus of any supply chain, and its relation is one of the key objectives of supply chain. Yet, CE aims to enhance sustainability in product development during its lifecycle. The second step involves forward supply chain view, which allows theorization of supply chain that product/service system is intended to be developed with. However, application of CE requires embodiment of R-strategies and that requires step three. It is likely to have overlaps between the defined enabling systems in each of the first three steps, hence at last step all the identified systems are integrated to cross-off the overlaps and identify the critical systems. This research suggests using some key concepts of the network theory to identify critical enabling systems in SC-CE-Context perspective proposed by this research. The first measure that can be used is the "betweenness centrality", which allows analysing of how frequently an enabling system interacts with other systems in supply chain SoSoI (the evolving dimension of supply chain due to dynamic integration of R-strategies) and likelihood of interacting with other systems at SC-CE context (including enabling social/technical systems beyond Supply chain SoSoI). The next measure that can be used is "eigenvector centrality", which considers the number of connections that an enabling system has with the systems that have high betweenness centrality. In network theory, it is argued that sometimes some nodes (systems in this research) that have the high number of connections with other nodes play a critical role within the network and must be planned carefully. Therefore, this research also suggests using this measure to analyse the Supply chain SoS and identify those enabling systems that due to a higher number of interactions with systems with high betweenness to maximize their efficiency and increase objective satisfaction at supply chain SoS and realization of CE objectives.

4. Discussion and Future Directions

Analysing a supply chain that employs CE-driven R-strategies increases complexity of evaluating the performance of activities along the nodes of that supply. The proposed theorization offers a perspective that enhances understanding of practitioners, researchers or policymakers about functional value that is created or "recuperated" in a closed loop supply chain as opposed to that of a linear supply chain. The total value of the closed loop supply chain is sum of the value in a product's initial linear supply chain and the value generated by the R-strategies implemented in the supply chain. The same can be computed with the measure of EIs. These two measurements first highlight an important distinction in how functional value is created along a CE supply chain. For the environmental efficacy of a supply chain to improve with implementation of R-strategies, EI of R-strategies should try to be as small as possible while capturing the most functional value possible. This can sound obvious but can be misunderstood operationally, namely because of a lack of data or limiting measurement system's scope. For example, a printer manufacturing company that has recently implemented a remanufacturing program by collecting older printers from customers might only measure EI of actual remanufacturing when evaluating their R-strategy without including impact of additional warehousing and transportation required. This highlights the importance of evaluating all supply chain changes that go into implementing a new R-strategy. The complexity can increase radically when many different strategies are implemented at the same time. The methodology proposed in this paper addresses this issue by assessing each R-strategy within a wider system. This may not reduce the complexity of wider system per se, but certainly helps stakeholders to better understand this complexity and not isolating the effects of individual strategies on whole of the system. By dichotomizing the analysis of a closed loop supply chain into what could be called traditional supply nodes and R-strategies, the proposed approach allows better understanding of how new measures affect the overall environmental efficacy of the system.

The amount of data generated by industries is growing exponentially coming from variety of sources as called big data [26], presenting opportunities/challenges. The need to analyze big data arises from its potential insights that can be used to optimize operations and improve customer experience [27]. Big data is often characterized by its overwhelming volume, fast velocity, uncertain veracity, and varied formats [26]. Hence, new approaches including digital twin and semantic web technologies have emerged to effectively collect, store, manage, and analyse it [28] . A digital twin is a digital replica of a physical object based on data and models [29], which can be used for virtual experiments, performance prediction, optimization, monitoring, control, and data management [28, 30]. For data management, a digital twin provides a platform for collecting, integrating, and analysing different data types from various sources [31, 32]. From this paper's perspective, a digital twin can support CE by enabling better data structuring [33] (e.g., composition, origin, and history of materials and products, current condition, and their potential for reuse or recycling) for integration of R-strategies with supply chain nodes. Digital twin can strengthen collaboration among stakeholders by increasing transparency and facilitating information flow at right stages [33]. Semantic web technologies like ontologies and knowledge graph can play a critical role in data management by facilitating structuring, sharing, and reuse of data [34, 35]. Semantic technology can enhance CE by supporting design of sustainable products with their EI modelling/assessment and analysing/tracking their pathways through a supply chain. This knowledge can be used to identify opportunities for R-strategies application. Further research are necessary to fully realize benefits of digital twin and semantic web technologies for CE realization different product types.

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1. Biography

Shiva Abdoli is a lecturer in School of Mechanical and Manufacturing Engineering, UNSW. She worked as a researcher in KTH University, Sweden. She received her Ph. D in 2019 from UNSW. After her post-doctoral fellowship, she started as a Lecturer in 2020 at UNSW. She has led industry-based research projects. Her research field includes System design, Industry 4.0, Sustainable Production, and Circular Economy.

Sijia Xie is a Master of Philosophy in the School of Mechanical and Manufacturing Engineering, UNSW. In 2022, she received her Master degree in Manufacturing Engineering and Management from UNSW. She is Casual Academic at UNSW. Her research interest includes Inventory management, Industry 4.0, Circular Economy, Supply chain management.

Bahador Bahramimianrood completed his Master's degree from Sichuan University in 2019. He is currently a Ph.D. student at the School of Mechanical and Manufacturing Engineering, University of New South Wales (UNSW), starting from 2023. His research interests focus on the Circular Economy, Industry 4.0, Sustainability and Optimization.

Mohammed Malaibari is a PhD student in the School of Mechanical and Manufacturing Engineering at UNSW Sydney. He holds a Master of Science in Mechanical and Manufacturing Engineering from UNSW Sydney. He worked as a researcher at Concordia University, Montreal. His main research interests are Digital Twin, Knowledge Graph, Data Management, Industry 4.0, and Circular Economy.

Thomas Stringer is a Professor in the Department of Industrial Engineering at Tecnológico de Monterrey. He holds a Ph.D. in Industrial Engineering from Polytechnique Montréal and his main research interests are public policy, transportation, energy economics and supply chain management. He previously completed his postdoctoral training at the University of British-Columbia.