# Designing Circular Supply Chains: A Requirements-Driven and CE-Centred System Design Methodology

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## ABSTRACT

### Introduction

The Circular Economy (CE) model aims to eliminate waste by coordinating collaborative stakeholder efforts throughout the life cycle to keep resources in circulation at the highest level and regenerate ecological systems. The shift towards circular resource flows contrasts to the linear consumption model, which has resulted in the depletion of resources and accumulation of waste (Lahane et al. 2020). Circular resource flows are increasingly being deployed through interventions such as shifting to renewable or secondary raw materials and adding reverse logistic operations to traditional supply chains (Mallick et al. 2024). These interventions create a circular supply chain (CSC) as they enhance resource efficiency and yield value for stakeholders through reduced material losses and energy conservation (Zeeuw van der Laan and Aurisicchio 2021). However, currently supply chain interventions are often introduced without a holistic plan to create circular value and departing from existing resource and system configurations that are challenging to change (Bressanelli et al. 2019; Burke et al. 2023). In addition, circular resource flows are often designed by few stakeholders, despite being increasingly acknowledged that collaboration and cooperation between all stakeholders are necessary and critical to achieve a CSC (Bressanelli et al. 2019; Gomes et al. 2024). Existing tools to facilitate the design of CSCs are inadequate as they do not support holistic design, following the three dimensions of sustainability (MahmoumGonbadi et al. 2021; Shahsavani and Goli 2023; Sassanelli et al. 2019). A gap exists in the literature with respect to tools to design CSCs from system requirements and provide tangible information on resource flows for easy system definition and performance measurement (Sassanelli et al. 2019; MahmoumGonbadi et al. 2021). Among others, tools are needed that can support CSC design in the early stages of the development process when alternative system configurations are likely to emerge and stakeholders must promptly define, test, verify and validate them (Burke et al. 2023; NASA 2017).

The aim of this paper is to propose a system design methodology for the concurrent design of a CSC and its resources, whilst allowing for stakeholder collaboration. The final methodology involves a comprehensive representation of resource flows to facilitate system design and assessment, establish performance of alternative system configurations and inform decision-making. Further, when the system performance is determined, the methodology has to enable verification of the system requirements and validation to check if stakeholders intent is met, providing a robust and practical approach to system design and resource management in alignment with CE principles.

### State of the Literature

Current literature has output both theoretical and mathematical models to aid the design of CSCs. Theoretical models provide a conceptual representation of a CSC based on CE principles and the relationships between supply chain elements, whereas mathematical models use analytical methods to optimise the supply chain network for specific system configurations (Lahane et al. 2020; MahmoumGonbadi et al. 2021). Theoretical models allow for the definition of the strategies underpinning a CSC, but they lack the capability to test alternative system configurations to inform decision-making (Lahane et al. 2020). In contrast, mathematical models are designed to support decision making; however, they are limited as they are often applied to a specific CSC system, e.g. logistics, rather than whole system

(Lahane et al. 2020; Shahsavani and Goli 2023, MahmoumGonbadi et al. 2021). They often lack the application to real-world cases and capturing the complexities of real-world issues is difficult in the formulation of the model (Shahsavani and Goli 2023). Interestingly, both theoretical and mathematical models focus on CSC design after the product has been developed and do not support stakeholder collaboration in the design process (Gomes et al. 2024; Burke et al. 2023; Amir et al. 2023; MahmoumGonbadi et al. 2021). There remains a lack of methodologies that allow concurrent modelling of CSCs alongside material, component and product flows, supporting iterative system design (Amir et al. 2023).

Decision-making must be informed by performance indicators; however, developing a methodology to assess CSCs is challenging due to the need to account for multiple CE performance indicators for effective trade-off analyses or multidisciplinary design optimisation (Sassanelli et al. 2019; Vegter et al. 2023; Ko et al. 2024). CE performance indicators typically encompass the entire spectrum of sustainability dimensions (MahmoumGonbadi et al. 2021): economic (e.g., profitability, total cost of ownership), social (e.g., wages), and environmental including both carbon impact (e.g., carbon footprint) and circularity (e.g., Material Circularity Indicator (MCI)).

## Methodology

The research aim is addressed by proposing a system design methodology for concurrent design of a CSC and its resources as a resource flow system (Zeeuw van der Laan and Aurisicchio 2021). This approach employs a loop between three stages (see Figure 1): 1) defining the system design based on the system requirements; 2) analysing the system design to derive the system performance; and 3) verifying and validating the requirements based on the system performance. Notably, the system requirements are modelled using the Holistic Requirements Model (HRM) (Burge 2006) and departing from the business value proposition (Amir et al. 2023; Mallick et al. 2024); the system design is generated using a new and CE-centred system modelling method; and the system performance is derived using sustainability indicators.

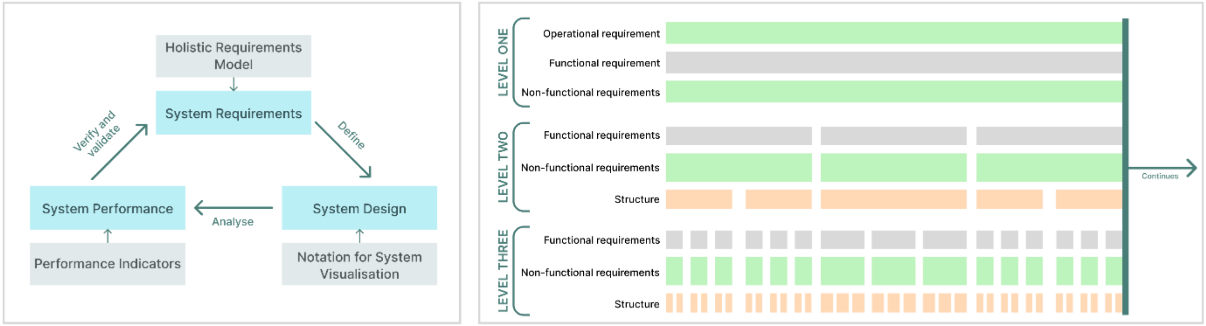

**Figure 1**. On the left, the System Design Methodology as a loop involving 3 stages; on the right, the method of defining the requirements and corresponding structures based on the Holistic Requirements Model.

*System Requirements and System Design using the HRM.* As a first step, the Level One requirements are defined (see Figure 1). This involves defining the Operational Requirement (OR), the Functional Requirement (FR), the Non-Functional Performance Requirements (NFPR) (established to set specific targets for the FRs), the Non-Functional Implementation Requirements (NFIR) (solutions to FRs demanded by the customer or legislation), and lastly the Non-Functional System Requirements (NFSR) (constraints that affect the whole or significant portion of the system and can be defined by stating the "-ilities" of the system). Following this, the FRs for the whole system are decomposed into the Level Two requirements and translated into the Level Two structures, i.e. systems (see Figure 1). The next step involves the definition of the Level Three requirements departing from the Level Two structures (see Figure 1). Once the Level Three requirements are defined, the FRs for each system are translated into the Level Three structures, i.e. the subsystems. Driven by the requirements specified at each level, the system design progresses from the higher to lower levels.

*System Design using a new and CE-centred system modelling method.* This work involves representing the systems and subsystems on a geographic map producing a network of nodes and flows. Nodes represent actors and infrastructure, while the flows track the movement of resources, data and value in the system (Zeeuw van der Laan and Aurisicchio 2021). The nodes have types (i.e. Material manufacturing, Component manufacturing, Assembly, Distribution, Use, Collection, Recovery) and parameters (Location, Time spent by the resource in the node, and Resource flow start). The connectivity between the nodes defines the flows, which also have parameters (Resource flow, Flow direction, Resource class in movement (material, component or product), and Transportation method). This visual representation method facilitates the definition, testing, verification and validation of the system design.

*System Performance using sustainability indicators.* This work entails determining the performance of the system using indicators. Comparing the performance outcomes to the targets, the requirements, e.g. NFPR, are verified and validated across the system hierarchy (NASA 2017). This process facilitates informed decision-making and insights into how and where the system can be enhanced.

## Application of the System Design Methodology to the Circular Supply Chain of a Furniture Product

The case study concerns the application of the system design methodology to the CSC of a future furniture product by a large UK-based company. The system performance was tested using three indicators namely carbon footprint, embodied energy and MCI. The data to apply the methodology was collected through several methods including document analysis, interviews and observations with notetaking.

To start with, the value proposition was defined as *developing a future system that allows furniture remanufacturing with a focus on circularity, affordability and responsibility*. For this purpose, a future furniture product is investigated with frame components made of oriented strand board (OSB) and particleboard and having a higher utility than the components in traditional furniture products to make them reusable over multiple use cycles. This means that the CSC requires introducing new nodes (actor and infrastructure) and flows (resource, data and value) to handle both the new forward and reverse logistics.

*System Requirements and System Design.* To define the Level One requirements, the OR was defined as *cycling resources for economic, environmental and social value*, while the FR as *flowing resource circularly*. The NFPRs are, for example, *decrease in carbon footprint*, *increase in MCI*, and *cost equal to or lower than that for the current system configuration*. The NFIRs include, for example, *ensure no reduction in product quality*, *minimise increase in costs for business and consumer* and *continue to employ people in the UK*. The NFSRs are, for example, *versatility* and *scalability*. To develop the Level Two requirements, the FR at Level One is then broken down into lower-level FRs such as *source, manufacture, assemble, distribute, retail, use, collect and recover* and non-functional requirements are also defined. From this the Level Two structures are proposed. These are made up of systems such as *sourcing system, manufacture system, assembly system*, etc.

Next, departing from the Level Two structures, the Level Three requirements are defined. For example, the FRs for the *particleboard material manufacture system* are *transport recycled wood waste to the manufacturer and manufacture the particleboard*, while for the *OSB material manufacture system*, the FRs are *harvest wood, transport raw wood to the manufacturer*, and *manufacture the OSB*. Various options to satisfy the FRs and therefore define the Level Three structures can be explored leading to alternative system configurations.

*System Design.* The CSC is then visualised on a geographical map, see Figure 2. The visualisation illustrates how the systems and subsystems for the CSC of the future furniture product are mapped as a network of nodes and flows over the UK. In Figure 2, the zoomed area (showing Scottish Lowlands) depicts in green the flow of particleboard over the *Collection*, *Recovery, Material manufacturing, Component manufacturing* and *Distribution* nodes and in orange the flow of the OSB over the *Material manufacturing, Component manufacturing* and *Distribution* nodes. As it can be seen, both flows are heading south and they join in the *Assembly* node (in the Midlands) where the furniture product is assembled. At the end of life of the furniture product, the OSB flow reverses, passing first through the *Distribution* and *Assembly* nodes, and then the *Collection* node. At this point the OSB frame components are assessed to understand whether they can be reused as components and if so, they are categorised in the *Collection* node for use in the *Assembly* node. Otherwise, they are sent to the *Recovery* node for recycling (with the flow colour changing from orange to green) and the materials subsequently shipped to the *Material manufacturing* node to make particleboard.

It is noteworthy that the system visualisation supports design of circular resource flows are reuse and recycling levels. For example, the OSB components can flow at the reuse level where undamaged components are recovered and reused in the manufacturing process or at the recycling level where they are recycled to produce particleboards. This shows how the visualisation enables to examine the geographic placement of nodes and flows within circular resource flows at different level, as well as the connections and locations of the involved actors.

*System Performance.* The system performance allows for analysis of system configurations and their assessment to select the most suitable system configuration. For example, in Figure 2, the nodes where the raw materials are transformed into OSB materials and components (Material manufacturing, Component manufacturing, Distribution and Assembly) are marked and scored with sustainability indicators (embodied energy and carbon footprint). Further, as the system configuration investigated in this case study keeps high the value of OSB frame components because they are reused into the manufacturing process for up to three product life cycles, the MCI is increased substantially, from 0.55 to 0.85 when compared to the current linear supply chain.

At each system design cycle, the CSC configuration is verified down to the lowest level requirements for all flows. Then it is validated to ensure coherence and fulfilment of the higher level requirements. System visualisation and performance facilitate stakeholder collaboration by providing an overview of the change, enabling detailed system analysis and evaluation of CSC nodes and flows. The methodology supports future enhancements and new developments, managing requirement volatility (Peña and Valerdi 2015), preventing rework and serving as a knowledge base, and aiding in information transfer to new designers and actors or further operations.

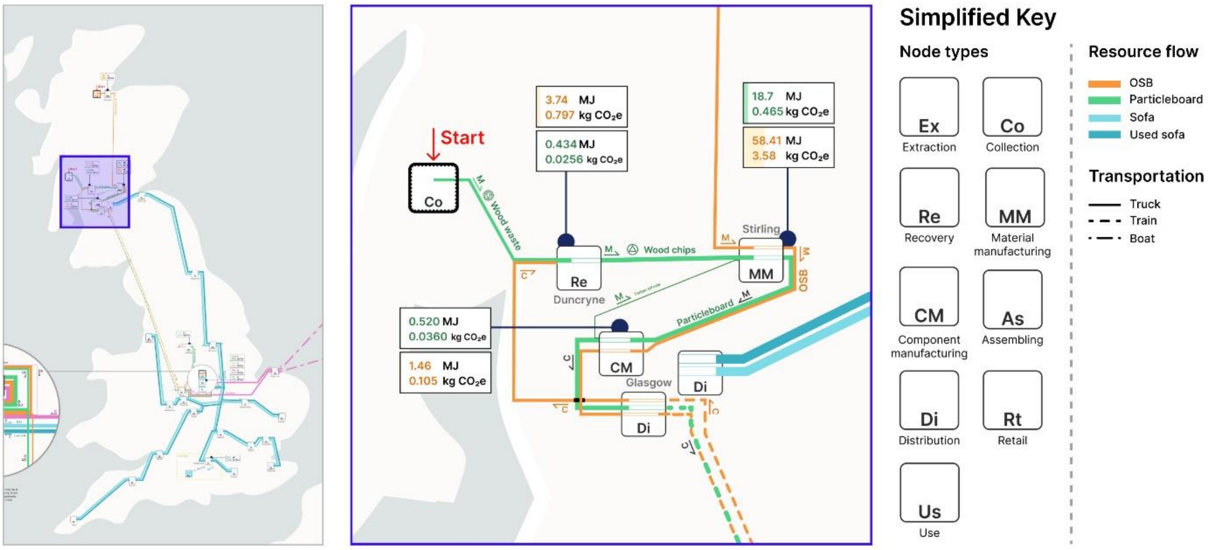

**Figure 2**. CSC design and visualisation for some of the nodes and flows for particleboard and OSB over a geographical map.

## Discussion and Conclusions

A new methodology for the design of CSC has been proposed integrating three components: a robust approach to requirements management supported by the HRM model; a new and CE-centred method and notation for system design and visualisation; and a mix of sustainability and circularity indicators to determine the system performance. The HRM model provided a holistic vision on the system, enabling the identification of system requirements early on and supporting requirements-driven system design. The method and notation for system design and visualisation made easy and straightforward to define alternative system configurations and compare them quantifying their impacts using the performance indicators. The methodology led to the development of a design for the CSC with significant improvements to the performance indicators compared to the existing design. Overall, the methodology facilitated a comprehensive top-down definition of the CSC, empowering decision making at each level. It also aided in understanding the risks posed by the design, informing future actions. Moreover, the methodology can support collaboration by stakeholders.

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