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Simulation-Based Measurement of Information Value in Circular Economy Networks

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***Abstract* – Circular economy networks require not only physical recovery capabilities, but also timely information about inventories, repair status, remanufacturing progress, and expected availability. Reusable products or components may already exist somewhere in the network, or may become available after repair or remanufacturing, but these resources cannot support fulfilment decisions if they remain informationally invisible. This paper proposes a simulation-based approach for measuring the operational value of information sharing in cooperative circular production networks. A demonstrative European spare-part fulfilment network is implemented in AnyLogic, including customer regions, distributors, service centres, collection points, repair centres, and remanufacturing capacity. Three information-sharing scenarios are compared: local decision-making without shared information, network-wide inventory sharing, and combined inventory and due-date sharing. The evaluation framework measures service reliability, quantity fulfilment, new production avoidance, delay, recovery utilisation, cost efficiency, inventory performance, emissions, and recovery rate. The contribution is a diagnostic simulation concept for identifying information gaps and evaluating how digital coordination can improve circular network performance.**

Keywords – Circular economy, value of information, information sharing, simulation, AnyLogic, remanufacturing, repair, closed-loop supply chain, diagnostics, Responsible Consumption and Production

I. INTRODUCTION

Circular economy implementation in manufacturing extends well beyond recycling or end-of-life recovery. Once products return from the field, they must be assessed, routed, and reintegrated through repair, remanufacturing, or redistribution into active fulfilment processes. This creates a class of operational dependencies that has no direct equivalent in linear supply chains. Recovered items may be geographically dispersed, in varying states of condition, and only become usable after processing delays of uncertain length. The practical consequence is that circularity is not purely a materials problem; it is equally a problem of operational visibility.

What makes this particularly challenging is that physical availability does not imply decision-making availability. A repaired component may exist in the network and become ready before a customer's due date, yet trigger unnecessary new production simply because no actor in the chain is aware of it. A regional service point may place an emergency order while adequate stock sits idle at a nearby distributor. These are not failures of physical capacity but failures of information. The problem is especially acute in systems where repair and remanufacturing introduce a temporal gap between product return and renewed availability. If that expected future output is not visible to fulfilment logic, circular resources remain operationally inaccessible even when they are physically present.

This paper proposes a simulation-based approach for measuring the operational value of information sharing in a cooperative circular economy network. Three information-sharing scenarios are compared within a fixed physical topology and demand structure, so that observed performance differences can be attributed directly to differences in information availability. The evaluation covers service reliability; circularity indicators such as new production avoidance and recovery rate; and economic and environmental performance. Rather than treating information sharing as a qualitative best practice, the proposed framework attempts to quantify how different levels of visibility alter fulfilment decisions. The work is positioned as a proof-of-concept that can be calibrated with industrial data in subsequent research.

II. RELATED RESULTS IN THE LITERATURE

The circular economy literature has converged on a shared understanding that resource loops must be closed, slowed, and narrowed by extending product life and reducing dependence on virgin material inputs [1]. Translating this into production systems requires more than strategic intent; it demands operational mechanisms for reuse, repair, refurbishment, remanufacturing, and recycling, each of which involves a distinct set of actors, timelines, and coordination requirements. The diversity of definitions and conceptual framings surrounding the circular economy reflects how broad this transition is in practice [2]. As Farooque et al. [3] note, circular supply chain management cannot be reduced to a material-flow problem. It requires information exchange and decision support structures that actively enable recirculation across network boundaries. In spare part networks specifically, this uncertainty is compounded by the fact that demand for remanufactured components is often driven by installed base dynamics rather than by predictable market signals.

The foundational literature on reverse logistics and closed-loop supply chains established many of the core challenges relevant to this context. Fleischmann et al. [4] demonstrated that return flows introduce planning complexity well beyond what forward supply chain models address, primarily because recovered products are heterogeneous in timing, quantity, and reuse potential. Govindan et al. [5] extended this perspective through a comprehensive review showing that recovery systems require specific coordination mechanisms to manage the uncertainty inherent in collection, sorting, and reprocessing decisions. These insights remain relevant for circular production networks, where the coordination challenge is compounded by the need to connect demand, inventory, ongoing repair processes, and expected future availability within a single decision framework.

The role of information in this context has received growing attention. Jäger-Roschko and Petersen [11] synthesised 84 peer-reviewed articles on information sharing in circular economy settings and found that interorganisational visibility is a prerequisite for keeping materials and products in the loop. Without reliable information on what exists, where it is, and when it will be ready, circular resources cannot be effectively assigned to demand. Zhang et al. [12] examined information sharing in a closed-loop supply chain with dual recycling channels and showed that the value of downstream demand information to upstream remanufacturing decisions depends on market conditions and channel power structure. Khan and Abonyi [13] approached the same problem from a digital infrastructure perspective, arguing that supply chain interoperability is a structural condition for circular economy goals, particularly under Industry 5.0 principles.

Simulation has emerged as a natural methodological choice for studying these systems, precisely because circular production networks are dynamic and distributed in ways that static optimisation models cannot capture [6], [7]. Agent-based and discrete-event approaches can represent inventory states, repair lead times, return flow variability, and local decision logic simultaneously. Lieder et al. [8] used agent-based simulation to explore how business models can be adapted toward circular economy implementation, while Roci et al. [9] demonstrated that multi-method simulation enables more realistic decision support in circular manufacturing contexts. Salehi et al. [10] developed an integrated analysis framework for circular supply chains that positions simulation as a tool for evaluating operational performance rather than solely for network design optimisation. Massari et al. [14] further extended this line of work by modelling circular supply chains as complex adaptive ecosystems, showing that the interaction between information flows and network structure determines how effectively circular resources are used.

A specific gap remains in the literature concerning the operational value of due-date information in spare part fulfilment networks. Gupta et al. [15] showed that accurate demand forecasting for remanufactured parts is critical for inventory optimisation across distribution networks, and that information deficits lead directly to delayed fulfilment or costly substitution with new parts. The present paper addresses a related but distinct question: not how to forecast demand for remanufactured parts, but how visibility into expected repair and remanufacturing output changes the fulfilment decisions that are made before that output becomes available.

III. DESCRIPTION OF THE METHOD

The simulation model was implemented in AnyLogic as a demonstrative circular spare-part fulfilment network covering a set of European regions. The network consists of customer regions, distributors, service centres, collection points, repair centres, and remanufacturing facilities, connected by directed transport links. Each link carries attributes for transport mode, distance, lead time, cost, and operational status. The topology follows a regional mesh structure rather than a hub-and-spoke configuration, a deliberate choice to avoid concentrating all routing decisions through a single central node. This matters because the operational value of a circular resource is not determined solely by its existence; it also depends on whether it can be reached within acceptable time and cost constraints from the point of demand.

The model captures both the forward fulfilment flow and the circular recovery logic running alongside it. Customer regions generate stochastic demand for spare parts. Distributors and service centres hold inventory available for immediate fulfilment. Collection points and service centres receive returned products and recoverable cores, which are then routed to repair centres or remanufacturing facilities depending on their condition. Once a repair or remanufacturing order is completed, its output re-enters the network as circular availability. The distinction between stock that is currently on hand and output that is expected at a future date is central to the design of the third scenario, since it is precisely this expected future availability that due-date information makes visible.

The network topology is illustrated in Fig. 1, which shows the geographical distribution of nodes and the transport links used for both fulfilment and return-flow routing. The figure also reflects a design choice worth noting: proximity to demand is not the only criterion for source selection. A service centre with limited stock but a short transport route may be a better fulfilment source than a distant distributor with larger inventory. The model therefore evaluates candidate sources on quantity, reachability, lead time, and transport cost jointly, rather than ranking them on availability alone.

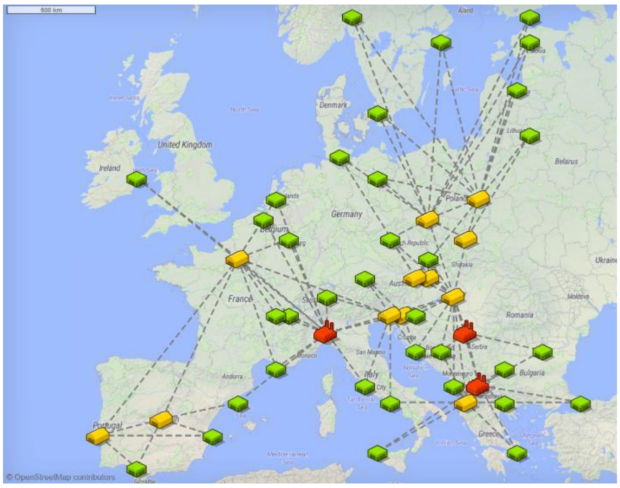

Fig. 1. Demonstrative European circular economy network used in the simulation model.

Three information-sharing scenarios structure the experimental comparison. In the first, no shared information exists; each customer region can draw only on its local inventory, and any unmet demand is immediately escalated to new production. This represents a baseline of fragmented decision-making, in which circular resources elsewhere in the network are physically present but operationally invisible. In the second scenario, network-wide inventory visibility is introduced. The fulfilment logic can now search across all nodes for currently available stock and select a source based on the joint criteria above. The third scenario adds due-date sharing to inventory sharing: when no suitable current stock is found, the model can also consider expected future output from active repair and remanufacturing orders, provided that output is projected to arrive before the customer's due date. The three scenarios therefore represent increasing levels of digital coordination, from isolated local decisions to network-wide visibility of both current stock and expected future output.

Performance is assessed through a multidimensional indicator framework designed to avoid redundancy across dimensions. Order service level captures whether orders are fulfilled at all; quantity fill rate measures the share of requested volume that is satisfied through circular sources. New production avoidance and recovery rate assess the circularity of fulfilment outcomes. Future availability utilisation tracks how much of the expected repair and remanufacturing output is actually assigned to demand, which is the indicator most directly sensitive to due-date information. Operational cost, transport cost per fulfilled unit, and average inventory level capture the economic consequences of each scenario. Estimated emissions and the overall recovery and recycling rate connect the operational results to environmental objectives. Together, these dimensions separate what the network delivers from how it delivers it and at what cost.

IV. EVALUATION AND EXPECTED RESULTS

The experimental design holds the physical network and demand structure constant across all three scenarios. Any difference in observed performance can therefore be attributed to differences in information availability rather than to differences in network capacity or demand volume. This controlled structure is the key property of the proposed diagnostic approach: it makes it possible to measure the operational value of information in isolation, without confounding it with changes to the material system.

The evaluation framework consists of the following indicator groups:

- Service performance: measured by order service level, indicating the share of customer orders fulfilled from circular sources.
- Quantity performance: measured by quantity fill rate, indicating the share of requested quantity fulfilled through circular resources.
- Circularity performance: measured by new production avoidance, showing how much demand can be satisfied without escalation to new production.
- Time performance: measured by average and maximum fulfilment delay, capturing whether circular fulfilment remains operationally feasible.
- Recovery performance: measured by future availability utilisation, indicating how effectively expected repair and remanufacturing outputs are assigned to demand.
- Economic performance: measured by total operational cost and transport cost per fulfilled unit, capturing the cost consequence of sourcing decisions.
- Inventory performance: measured by average inventory, showing the stock level required to support each information-sharing scenario.
- Environmental performance: measured by estimated emissions and recovery/recycling rate, linking operational decisions to environmental and circular economy objectives.

The expected direction of results follows from the structure of the scenarios. Under fragmented decision-making, each customer region is limited to locally visible stock, which is likely to produce artificial shortages even when suitable inventory or recoverable output exists elsewhere in the network. Introducing network-wide inventory sharing should reduce this effect by expanding the set of candidate fulfilment sources; however, this scenario still considers only resources that are currently available. The third scenario is expected to yield further improvement precisely because it makes future circular output visible before it enters finished inventory. By allowing the fulfilment logic to reserve expected repair or remanufacturing output against incoming demand, the model can avoid premature escalation to new production in cases where a circular alternative would have arrived in time.

The topology of the network interacts with these information effects in a way the framework is also designed to capture. The same unit of stock does not carry the same operational value from every location; its value depends on the transport route connecting it to demand, the lead time on that route, and whether its expected availability is known early enough to act on. This means that investments in information infrastructure and investments in transport network structure are not independent; their combined effect on circular fulfilment performance is what the proposed framework is designed to reveal.

V. CONCLUSIONS AND OUTLOOK

This paper proposed a simulation-based framework for measuring the operational value of information sharing in cooperative circular economy networks. Three scenarios were compared within a fixed physical topology, progressing from locally fragmented decision-making through network-wide inventory visibility to combined inventory and due-date sharing. The evaluation framework spans eight performance dimensions and is structured so that observed differences can be attributed directly to information availability rather than to changes in physical capacity.

The primary contribution is a diagnostic simulation concept that quantifies the operational consequences of specific information gaps, rather than recommending information sharing as a general principle. The current model is a proof-of-concept; subsequent work will focus on calibration using real industrial transaction data and on extending the model to include return quality, repair yield uncertainty, product heterogeneity, and capacity constraints.

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