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RESEARCH ARTICLE

Digital Value Chain as a Circular Control Architecture

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Abstract

The transition from linear production models to circular manufacturing systems requires more than technological recovery capability; it demands lifecycle-wide governance of information and decision-making. Despite extensive research on Digital Twins and Industry 4.0 technologies, the practical implementation of short-loop circularity – maintenance, repair, and remanufacturing – remains constrained by fragmented lifecycle data and recovery uncertainty. Existing literature largely treats digital technologies as isolated enablers rather than as components of an integrated circular control system.

This paper conceptualises the Digital Value Chain (DVC) as a lifecycle-spanning circular control architecture that regulates the transformation of product data into structured circular interventions. Using a conceptual research design based on structured synthesis and abstraction, the study develops a multi-layered framework comprising data acquisition, state estimation, circular intervention, and feedback-to-design layers. Building upon this architecture, hierarchical levels of digital circular enablement – informational, analytical, and decision – are formalised to explain how lifecycle transparency evolves into circular governance.

The framework further introduces an operational decision logic structured around feasibility gates that govern maintenance, repair, and remanufacturing pathways. By reframing short-loop circularity as an information-dependent control problem, this research advances digital manufacturing and circular economy theory beyond technology adoption narratives toward systemic lifecycle regulation. The proposed model provides a conceptual foundation for assessing digital-circular maturity in manufacturing systems and offers a structured basis for future empirical validation and simulation-based modelling.

Keywords Digital Value Chain · Short-Loop Circularity · Circular Control Architecture · Digital Manufacturing · Industry 4.0

1. Introduction

Manufacturing systems are increasingly pressured to transition from linear production models toward circular value retention strategies. While technological capabilities for product recovery, repair, and remanufacturing have significantly advanced, the practical implementation of short-loop circularity remains inconsistent and economically uncertain (Awan et al., 2022; Ghoreishi, 2023). The core limitation is not the absence of recovery technologies, but the fragmentation of lifecycle information across the manufacturing value chain (Z. Chen & Huang, 2021; Szaller et al., 2023).

Short-loop circularity – maintenance, repair, and remanufacturing – requires high-resolution knowledge of product identity, usage history, degradation patterns, and material composition (Ojha et al., 2024). In most industrial contexts, this information becomes partially inaccessible once products leave the production environment. As a result, circular decisions are often reactive, conservative, and risk-averse, leading to premature disposal rather than value-preserving intervention (Preut et al., 2021).

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In this study, short-loop circularity refers to value-retention strategies that preserve the functional integrity of products and components, particularly maintenance, repair, and remanufacturing. These strategies differ from long-loop circularity, such as recycling, which focuses on material recovery rather than functional value preservation. Short-loop approaches typically require higher levels of lifecycle information and decision coordination, making them strongly dependent on digital integration.

Digital transformation initiatives, commonly framed within Industry 4.0, have introduced enabling technologies such as IoT sensing, Digital Twins, and data-driven analytics. However, existing literature largely conceptualises these technologies as isolated tools rather than as components of lifecycle-wide control architecture (Sajadieh & Noh, 2025). Despite increasing attention to digitalisation in circular manufacturing, existing research predominantly focuses on individual technologies such as Digital Twins, IoT, or data analytics as isolated enablers. However, there remains a lack of conceptual understanding of how these technologies can be integrated into a lifecycle-wide governance structure that systematically supports short-loop circularity. In particular, prior studies do not sufficiently explain how digitalisation coordinates information flows and decision-making across Beginning-of-Life, Middle-of-Life, and End-of-Life stages. (Ghoreishi, 2023; Jebbor et al., 2025; Scholtysik et al., 2025). Therefore, the central research question of this study is: “How can the Digital Value Chain be conceptualised as a lifecycle-wide control architecture that enables short-loop circularity in manufacturing systems?”

This paper addresses this gap by conceptualising the Digital Value Chain (DVC) as a circular control architecture. Rather than defining the DVC as a technological collection, it is interpreted as an integrated information and decision infrastructure that regulates short-loop interventions across the product lifecycle (Awan et al., 2022; Scholtysik et al., 2025). The central contribution of this research is the development of a structured Circular Control Loop Model, supported by hierarchical levels of digital circular enablement and operational decision logic for manufacturing systems. By reframing circularity as an information-governed control problem, this paper provides a theoretical foundation for transitioning from fragmented digital applications to coordinated lifecycle intelligence in manufacturing.

The remainder of the paper is structured as follows. Section 2 describes the conceptual research design and methodological approach. Section 3 presents the proposed Digital Value Chain framework and its operational logic. Section 4 discusses the theoretical implications and positions the framework within existing literature. Section 5 concludes the paper and outlines future research directions.

2. Methods (Conceptual Research Design)

This study adopts a conceptual research design aimed at theory development through structured abstraction of existing literature. Rather than testing hypotheses empirically, the methodological objective is to systematically derive a conceptual framework that explains how Digital Value Chains enable short-loop circularity in manufacturing system. The literature review follows a structured conceptual synthesis approach rather than a formal systematic review protocol. The aim is to identify recurring functional roles and conceptual relationships across the literature, rather than to provide exhaustive coverage of all publications.

2.1. Literature Scope and Selection Approach

A structured literature review was conducted to identify the key constructs relevant to the study. The review focused on three primary research domains:

- digital transformation in manufacturing (Industry 4.0, Digital Twins, IoT, data-driven systems),
- circular manufacturing and remanufacturing systems,
- lifecycle integration and closed-loop value chains.

The literature was sourced primarily from scientific databases such as Scopus, Web of Science, and Google Scholar. Keywords included combinations of “digital manufacturing”, “Digital Twin”, “circular economy”, “remanufacturing”, “lifecycle data”, and “closed-loop supply chain”.

The selection process prioritised peer-reviewed journal articles and conference papers that addressed lifecycle data, circular recovery processes, and digital integration mechanisms. Rather than aiming for exhaustive coverage, the review focused on identifying recurring patterns and conceptual relationships across the literature.

2.2. Abstraction and Framework Construction Logic

The framework was developed through an abstraction process that translated technology-specific implementations into technology-neutral functional capabilities. First, manufacturing activities were structured into three lifecycle phases – Beginning-of-Life (BoL), Middle-of-Life (MoL), and End-of-Life (EoL) – to ensure comprehensive lifecycle coverage (S. Chen & Tang, 2024; Preut et al., 2021). Second, digitalisation-related concepts were grouped into higher-level capabilities that enable continuity of information across these phases. Finally, circular outcomes were constrained to short-loop mechanisms, allowing the framework to focus on the highest-value retention strategies that are most dependent on granular lifecycle information (Mügge et al., 2024; Ojha et al., 2024; Szaller et al., 2023).

A key guiding assumption of the framework construction is that circularity in manufacturing is constrained primarily by information fragmentation and decision uncertainty across the lifecycle. Consequently, the framework conceptualises the Digital Value Chain as a lifecycle-wide control infrastructure that transforms data availability into circular interventions through staged enablement (Z. Chen & Huang, 2021; Sajadieh & Noh, 2025).

The conceptual framework was developed through a multi-step abstraction process.

First, recurring structural challenges in circular manufacturing were identified across the literature. These included limited lifecycle transparency, uncertainty in condition assessment, and unpredictability of recovery feasibility .

Second, recurring digital functions described in prior research were grouped into higher-level functional roles. These included data acquisition, lifecycle monitoring, predictive assessment, and decision support.

Third, these challenges and functions were abstracted into conceptual components forming the basis of the proposed framework. Specifically:

- three types of uncertainty were derived to describe the structural limitations of short-loop circularity,
- four functional layers were defined to represent the control architecture of the Digital Value Chain,
- three hierarchical enablement levels were introduced to explain the transformation from data availability to circular decision-making.

This abstraction process allows the framework to remain technology-neutral while preserving conceptual consistency with existing literature.

2.3. Theoretical Foundations of the Digital Value Chain Framework

The proposed Digital Value Chain (DVC) Circularity Model is grounded in three complementary theoretical perspectives: value chain theory, information asymmetry theory, and cyber-physical systems theory. The integration of these perspectives provides a structured conceptual basis for explaining how digital infrastructures enable circular economy mechanisms in manufacturing systems.

The framework is grounded in three complementary theoretical perspectives:

- value chain theory, which explains how value is created and retained across lifecycle stages,
- information asymmetry theory, which explains uncertainty in recovery decisions due to incomplete information,
- cyber-physical systems theory, which explains the integration of physical assets and digital representations.

These theoretical perspectives informed the interpretation of the abstracted components. Specifically:

- value chain theory provided the lifecycle structure (BoL–MoL–EoL),
- information asymmetry theory informed the identification of uncertainty types and the role of informational enablement,
- cyber-physical systems theory supported the interpretation of digital capabilities as lifecycle-wide control mechanisms.

The integration of these perspectives enabled the conceptualisation of the Digital Value Chain as a circular control architecture.

2.3.1. Value Creation and Value Retention in the Extended Value Chain The foundation of this framework builds upon classical value chain theory, which conceptualises manufacturing as a sequence of interrelated activities that create value for customers. While models focus primarily on value creation within linear production systems, circular economy principles extend this logic toward value retention across the product lifecycle (Awan et al., 2022).

In circular manufacturing, value is not only created during production but preserved through maintenance, repair, and remanufacturing activities. This lifecycle-wide perspective aligns with contemporary extensions of the value chain concept toward servitisation and product-service systems, where economic value is captured during the use phase and beyond (Awan et al., 2022; Ojha et al., 2024).

However, traditional value chain models do not account for the informational infrastructure required to sustain such extended value retention. The Digital Value Chain concept introduced in this study addresses this limitation by embedding a continuous digital thread across Beginning-of-Life (BoL), Middle-of-Life (MoL), and End-of-Life (EoL) stages (Mügge et al., 2024; Preut et al., 2021; Scholtysik et al., 2025). In this sense, the DVC can be interpreted as an evolution of value chain theory in the context of digital transformation and circularity

2.3.2. Information Asymmetry in Closed-Loop Manufacturing Systems A second theoretical pillar of the framework is information asymmetry theory, which explains market inefficiencies arising from unequal information distribution between actors. In closed-loop manufacturing systems, information asymmetry manifests in uncertainty regarding product condition, usage history, and material composition (Z. Chen & Huang, 2021).

Remanufacturing literature has repeatedly identified uncertainty concerning the quality of returned cores as a primary operational barrier. When manufacturers lack reliable data on component degradation or remaining useful life, remanufacturing becomes economically risky and inspection intensive. This uncertainty often results in premature recycling or disposal, thereby undermining circular economy objectives (Massari et al., 2023; Reich et al., 2024).

From this perspective, circularity is not solely a material flow problem but fundamentally an information problem (Preut et al., 2021). The Digital Value Chain addresses this asymmetry by enabling transparency (visibility of product state) and traceability (documentation of lifecycle history). Informational enablement therefore functions as a prerequisite for short-loop circular strategies. Without resolving information asymmetry, higher-level analytical and decision mechanisms cannot operate effectively (Tsolakis et al., 2023).

2.3.3. Cyber-Physical Systems and Digital Twin Theory The third theoretical perspective underpinning the framework derives from cyber-physical systems (CPS) and digital twin theory. CPS research conceptualises manufacturing systems as interconnected networks of physical assets and digital representations capable of real-time interaction. Digital twins extend this concept by enabling dynamic virtual modelling of asset behaviour throughout the lifecycle (González-Herbón et al., 2024; Redelinghuys et al., 2020).

Within this theoretical lens, the Digital Value Chain can be interpreted as a lifecycle intelligence infrastructure. Informational enablement corresponds to data acquisition and synchronisation within the cyber layer (Preut et al., 2021). Analytical enablement reflects the simulation and predictive modelling capacities of digital twins. Decision enablement represents the execution layer, where insights are translated into operational interventions (Elbasheer et al., 2025; Kang et al., 2020).

By integrating CPS theory with circular economy logic, the framework shifts digitalisation from a productivity-focused paradigm toward a resource-preservation paradigm. Digital technologies are therefore conceptualised not as isolated optimisation tools, but as systemic enablers of regenerative manufacturing (Mügge et al., 2024).

The integration of these three theoretical streams provides a coherent foundation for the proposed framework: value chain theory explains where value is created and retained; information asymmetry theory explains why circular loops fail without transparency; cyber-physical systems theory explains how digital infrastructures enable lifecycle intelligence. Together, these perspectives justify the conceptualisation of the Digital Value Chain as a multi-level enablement architecture that transforms fragmented lifecycle activities into an integrated circular system.

2.4. Derivation of the Conceptual Framework

The final framework was constructed by mapping the identified functional roles and structural challenges into a coherent control architecture. The four-layer structure of the Digital Value Chain was derived by grouping recurring digital functions into sequential roles:

1. Data Acquisition – capturing lifecycle data,
2. State Estimation – interpreting product condition and degradation,
3. Circular Intervention – enabling structured recovery decisions,
4. Feedback-to-Design – reintegrating lifecycle insights into future product development.

The hierarchical enablement levels were derived to explain how these layers progressively transform lifecycle data into circular action. Finally, the operational decision logic was formalised as a sequence of feasibility gates linking informational availability, technical feasibility, and intervention selection. This structured derivation ensures transparency in how the framework components were developed from the literature and integrated into a coherent conceptual model.

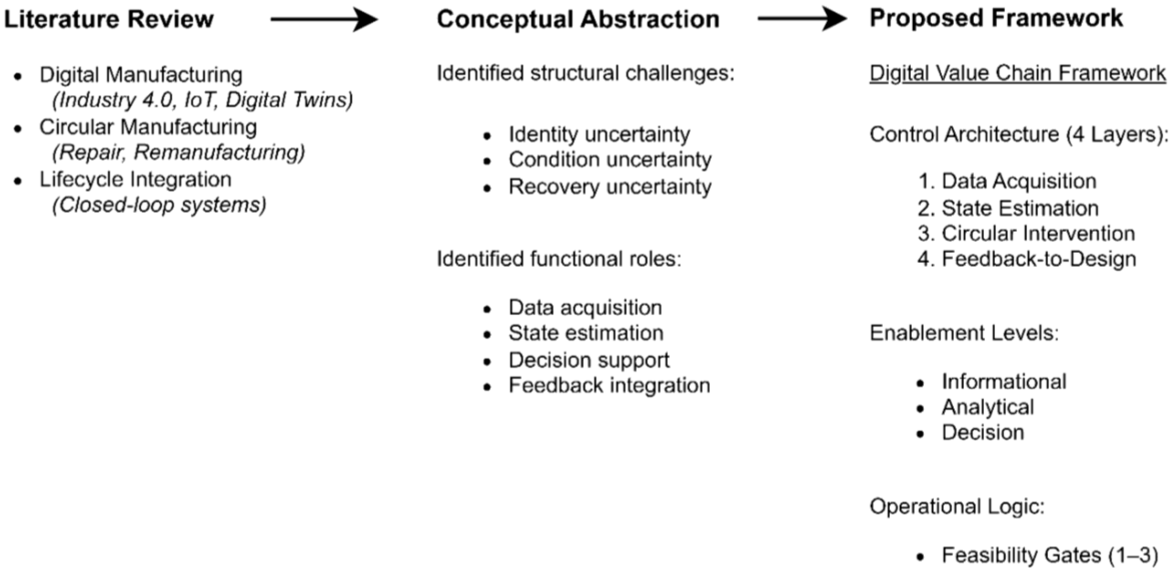

Figure 1. Derivation of the Digital Value Chain Circular Control Architecture

Figure 1 illustrates the derivation of the proposed Digital Value Chain framework. The model is constructed through conceptual abstraction of recurring patterns identified in the literature, including structural uncertainties and functional roles of digital technologies. These elements are synthesised into a circular control architecture with hierarchical enablement levels and operational decision logic.

3. Results

This section presents the conceptual framework derived through the abstraction process described in Section 2. The results translate recurring patterns identified in the literature into a structured control architecture of the Digital Value Chain.

Specifically, the framework is constructed by linking three key elements:

1. structural challenges of circular manufacturing identified as lifecycle uncertainties,
2. functional roles of digital technologies grouped into architectural layers,
3. and decision mechanisms formalised through hierarchical enablement levels and feasibility gates.

This structure ensures a transparent connection between literature-based insights and the proposed conceptual model. The framework therefore translates theoretical insights into a structured representation of lifecycle control logic for circular manufacturing.

The following subsections present the framework components in detail, describing the formalisation of the Digital Value Chain as a circular control architecture for manufacturing systems. The results articulate how lifecycle fragmentation constrains short-loop circularity and how an integrated digital architecture systematically addresses this constraint. (Z. Chen & Huang, 2021; Szaller et al., 2023).

The section proceeds in five stages. First, the structural problem of information fragmentation across lifecycle phases is clarified (Section 3.1). Second, the Digital Value Chain is conceptualised as a multi-layered control architecture (Section 3.2). Third, hierarchical levels of digital circular enablement are introduced to explain the progressive transformation of lifecycle data into circular governance (Section 3.3). Fourth, an operational decision logic formalises the feasibility gates governing short-loop interventions (Section 3.4). Finally, the framework is consolidated through a structured tabular and visual representation (Section 3.5). Together, these elements constitute the conceptual framework proposed by this study.

3.1. Information Fragmentation as a Structural Constraint to Short-Loop Circularity

The first step in the framework development was the identification of recurring structural barriers to short-loop circularity. Based on the literature synthesis, these barriers were consistently associated with discontinuities in lifecycle information and uncertainty in recovery decisions.

Through conceptual abstraction, these barriers were grouped into three types of uncertainty: identity uncertainty, condition uncertainty, and recovery uncertainty. These categories reflect recurring issues discussed in circular manufacturing and remanufacturing research, particularly related to traceability, condition assessment, and feasibility of recovery operations.

Short-loop circularity in manufacturing systems is frequently discussed in terms of technical recovery capability. However, the primary structural limitation is not the absence of repair or remanufacturing technologies, but the fragmentation of lifecycle information across value chain stages (Z. Chen & Huang, 2021).

In conventional manufacturing systems, Beginning-of-Life (BoL), Middle-of-Life (MoL), and End-of-Life (EoL) activities operate under partially disconnected information regimes. Design specifications, material compositions, and production parameters generated during BoL are rarely synchronised with real-time operational data from MoL. Similarly, insights derived from product recovery or failure at EoL are seldom reintegrated into future design decisions in a structured manner (Mügge et al., 2024; Sajadieh & Noh, 2025).

This fragmentation generates three forms of uncertainty:

1. **Identity Uncertainty** – ambiguity regarding product configuration and component traceability.
2. **Condition Uncertainty** – limited visibility into degradation patterns and usage history.
3. **Recovery Uncertainty** – unpredictability concerning the technical and economic feasibility of remanufacturing.

As a consequence, short-loop interventions such as repair or remanufacturing become risk-intensive decisions. Manufacturers often lack sufficient lifecycle intelligence to justify recovery investments, leading to conservative strategies such as material recycling or disposal.

The structural constraint is therefore informational rather than technological. Circularity requires not only recovery capability, but also continuity of data and decision logic across lifecycle stages. Without an integrated information infrastructure, circular actions remain reactive, fragmented, and inconsistent. This insight motivates the conceptualisation of the Digital Value Chain as a circular control architecture, presented in the following subsection.

3.2. Digital Value Chain as a Circular Control Architecture

Following the identification of structural uncertainties, the next step was to define how digital capabilities address these limitations. The literature consistently describes digital technologies in terms of their functional roles rather than isolated tools.

Through abstraction, these roles were grouped into four sequential functions: data acquisition, state estimation, intervention decision, and feedback integration. These functions were formalised as four layers of a circular control architecture, representing the operational logic of the Digital Value Chain across the product lifecycle.

The Digital Value Chain (DVC) is conceptualised in this paper as a collection of isolated digital tools, but as a lifecycle-wide circular control architecture. This architecture regulates the transition from fragmented lifecycle data to coordinated short-loop circular interventions. By interpreting digitalisation as a control system rather than as technological enhancement, the framework provides a structured explanation of how information continuity enables circular decision-making.

Short-loop circularity – maintenance, repair, and remanufacturing – requires coordinated interventions across Beginning-of-Life (BoL), Middle-of-Life (MoL), and End-of-Life (EoL) stages (Ojha et al., 2024; Sajadieh & Noh, 2025). These interventions cannot be executed reliably without structured data flows, state estimation, and feedback mechanisms. The DVC therefore functions as a multi-layered architecture consisting of four interdependent layers: Data Acquisition, State Estimation, Circular Intervention, and Feedback-to-Design.

3.2.1. Data Acquisition Layer The Data Acquisition Layer forms the foundation of the circular control architecture. It ensures that product-specific information generated across the lifecycle is captured, synchronised, and preserved.

At the BoL stage, this includes design specifications, material composition, manufacturing tolerances, and configuration parameters. During MoL, operational data such as usage patterns, service history, load profiles, and environmental conditions are continuously recorded. At EoL, inspection results, component degradation data, and disassembly observations provide further insights into product performance (Mügge et al., 2024; Szaller et al., 2023).

Without this structured acquisition of lifecycle data, circular decision-making remains speculative. Manufacturers are forced to rely on visual inspection, probabilistic assumptions, or conservative default strategies (e.g., disposal rather than recovery) (Z. Chen & Huang, 2021). The Data Acquisition Layer therefore functions as the informational prerequisite for circular feasibility. It transforms the value chain from a discontinuous sequence of activities into a traceable lifecycle continuum.

3.2.2. State Estimation Layer While data acquisition provides visibility, circularity requires interpretability. The State Estimation Layer transforms raw lifecycle data into structured assessments of component condition and recovery potential.

At this layer, digital representations such as Digital Twins or virtual models are used to estimate Remaining Useful Life (RUL), identify degradation mechanisms, and evaluate structural integrity (Preut et al., 2021). State estimation distinguishes between observable conditions and actionable feasibility. For example, although usage data may indicate wear, analytical modelling determines whether this wear is reversible through repair or whether it exceeds remanufacturing thresholds.

The key function of this layer is uncertainty reduction. Short-loop circularity is often economically unattractive due to risk – uncertainty about the quality of returned components, required labour intensity, or likelihood of secondary failure. By providing predictive assessment rather than retrospective diagnosis, the State Estimation Layer reduces this uncertainty and increases confidence in recovery decisions.

Without state estimation capabilities, lifecycle transparency alone does not guarantee circularity. Informational visibility must be converted into technical feasibility assessment to enable structured intervention.

3.2.3. Circular Intervention Layer The Circular Intervention Layer represents the decision and execution domain of control architecture. At this stage, the system determines and initiates the most appropriate short-loop intervention based on the outputs of the previous layers.

Interventions may include:

- Maintenance, when proactive servicing extends the Middle-of-Life phase.
- Repair, when functional restoration prevents premature transition to End-of-Life.
- Remanufacturing, when end-of-life components can be industrially restored to “like-new” condition and reintroduced into the Beginning-of-Life phase.

The selection among these options is governed by a multi-criteria logic balancing technical feasibility, economic viability, and environmental impact (Ojha et al., 2024). Importantly, the Circular Intervention Layer does not imply full automation. Rather, it provides structured decision support that reduces ambiguity and prevents reactive or ad hoc circular actions.

In the absence of this coordinated intervention layer, even accurate state estimation may fail to translate into circular outcomes. Information and analysis must culminate in structured execution to close the loop.

3.2.4. Feedback-to-Design Layer The final layer closes the circular control loop by systematically reintegrating insights from MoL and EoL back into the BoL stage. This feedback mechanism transforms circularity from a recovery activity into a design-oriented learning process.

Data on recurring failure modes, component fatigue, disassembly complexity, and repair bottlenecks inform design-for-circularity strategies (More & Buktar, 2025). Over time, products are reconfigured to enhance modularity, standardisation, reparability, and remanufacturability.

This layer ensures that circularity evolves from corrective intervention toward preventive optimisation. Without structured feedback-to-design integration, circular activities remain isolated operational events rather than drivers of systemic improvement.

3.2.5. The Control Logic of the Architecture The four layers together form a closed-loop control system:

- Data Acquisition establishes lifecycle transparency.
- State Estimation reduces uncertainty through predictive assessment.
- Circular Intervention executes structured short-loop decisions.
- Feedback-to-Design improves future product generations.

This architecture reframes short-loop circularity as a regulated lifecycle process rather than as an end-of-life strategy. The Digital Value Chain thus operates as the enabling infrastructure that governs information flows, decision thresholds, and recovery actions across the manufacturing lifecycle.

By conceptualising DVC as a circular control architecture, this framework moves beyond technology-centric narratives and provides a structured explanation of how digital integration systematically enables value retention in manufacturing systems.

3.3. Hierarchical Levels of Digital Circular Enablement

While Section 3.2 conceptualised the Digital Value Chain as a circular control architecture, the effectiveness of this architecture depends on the degree to which lifecycle information is progressively transformed into circular action. To formalise this progression, this paper introduces three hierarchical levels of digital circular enablement: Informational, Analytical, and Decision Enablement.

These levels do not represent technologies, maturity stages, or organisational structures. Rather, they describe the functional depth to which the control architecture is operationalised within manufacturing systems.

3.3.1. Level 1 – Informational Enablement (Lifecycle Transparency) Informational enablement corresponds to the basic functionality of the Data Acquisition Layer within the circular control architecture. At this level, the Digital Value Chain ensures that product identity, configuration, material composition, and usage history remain traceable across lifecycle stages.

The core function of this level is the reduction of information asymmetry (Z. Chen & Huang, 2021; Preut et al., 2021). In traditional manufacturing systems, once a product leaves the production environment, its condition and operational context become partially opaque. This opacity increases uncertainty regarding recovery potential and often results in conservative decision-making, favouring disposal over restoration.

Informational enablement establishes lifecycle transparency, but it does not guarantee circularity. It answers the question: ***What is known about the product?***

Without this level, short-loop circularity is structurally infeasible. However, informational enablement alone remains insufficient for structured intervention, as knowledge of history does not automatically determine technical recoverability.

3.3.2. Level 2 – Analytical Enablement (Lifecycle Understanding) Analytical enablement corresponds to the State Estimation Layer of control architecture. At this level, lifecycle data is transformed into condition assessment and predictive insight. This includes estimation of Remaining Useful Life (RUL), identification of degradation mechanisms, and evaluation of structural thresholds relevant to maintenance, repair, or remanufacturing (Sajadieh & Noh, 2025). Analytical enablement answers a fundamentally different question than informational enablement: ***Given what is known, what is technically feasible?***

This level distinguishes between data availability and recovery potential. A product may be fully traceable, yet analytically unsuitable for remanufacturing due to irreversible fatigue or contamination. Conversely, predictive modelling may reveal that intervention is viable before catastrophic failure occurs, enabling proactive maintenance. Without analytical enablement, circular decisions remain reactive and risk-prone. Informational visibility without interpretive modelling results in conservative default strategies and missed opportunities for value retention.

3.3.3. Level 3 – Decision Enablement (Lifecycle Governance) Decision enablement corresponds to the Circular Intervention Layer of architecture. At this level, informational and analytical outputs are synthesised into structured short-loop decisions.

The role of decision enablement is not merely computational optimisation, but lifecycle governance. It integrates technical feasibility, economic implications, and environmental considerations to select the most appropriate circular pathway (Awan et al., 2022). Decision enablement answers the final control question: ***Which circular intervention should be executed?***

This may result in:

- Preventive maintenance to extend the Middle-of-Life phase,
- Targeted repair to restore functionality,
- Remanufacturing to reintroduce components into the Beginning-of-Life phase.

Without this level, even advanced state estimation fails to translate into circular action. Manufacturing systems may possess predictive insight yet lack structured mechanisms for operationalising recovery decisions.

3.3.4. Interdependence of Enablement Levels The three levels form hierarchical progression rather than independent capabilities. Informational enablement is a necessary but insufficient condition for circularity. Analytical enablement builds upon informational transparency by reducing uncertainty regarding recovery potential. Decision enablement integrates both layers into lifecycle-wide governance.

The absence of any level constrains the circular control architecture:

- Without informational enablement, recovery decisions are speculative.
- Without analytical enablement, circular actions are risk-averse and conservative.
- Without decision enablement, circularity remains fragmented and reactive.

By formalising these dependencies, the framework clarifies that short-loop circularity is not a binary state but a function of digital enablement depth. The Digital Value Chain becomes circularly effective only when lifecycle transparency, predictive assessment, and structured intervention are coherently integrated.

3.4. Operational Decision Logic for Short-Loop Circularity

While the previous sections defined the structural architecture and hierarchical enablement levels of the Digital Value Chain, practical circularity requires a structured decision sequence. This subsection translates the conceptual model into an operational decision logic that governs short-loop interventions across the manufacturing lifecycle.

The proposed logic does not represent a computational algorithm. Instead, it formalises the sequence through which lifecycle data is progressively transformed into circular action. The decision logic is structured around three consecutive feasibility gates corresponding to the hierarchical levels of enablement.

3.4.1. Gate 1 – Informational Feasibility The first decision gate evaluates whether a short-loop intervention is informationally viable. At this stage, the system assesses the availability and completeness of lifecycle data required for circular evaluation.

Key assessment questions include:

- Is the product or component uniquely identifiable?
- Is its configuration traceable?
- Is usage and service history accessible?
- Is material composition documented?

If the required data is incomplete or inaccessible, circular decision-making becomes economically uncertain due to high inspection costs and unpredictable quality outcomes (S. Chen & Tang, 2024). In such situations, manufacturers typically default to conservative strategies, including recycling or disposal.

Passing Gate 1 does not guarantee circular recovery, it merely establishes that the informational preconditions for further assessment are satisfied.

3.4.2. Gate 2 – Technical Feasibility Assessment If informational feasibility is established, the decision process advances to analytical evaluation. At this stage, the State Estimation Layer determines whether short-loop recovery is technically feasible.

This involves:

- Estimating Remaining Useful Life (RUL)
- Evaluating degradation mechanisms
- Assessing structural integrity
- Determining compatibility with remanufacturing standards

The purpose of Gate 2 is to reduce technical uncertainty. A component may be fully traceable yet analytically unsuitable for remanufacturing due to irreversible fatigue, contamination, or dimensional deviation beyond tolerance.

If analytical evaluation indicates that recovery thresholds are exceeded, the intervention is downgraded to lower-value pathways. If technical feasibility is confirmed, the system proceeds to structured decision selection.

3.4.3. Gate 3 – Circular Intervention Selection The third gate synthesises informational and analytical outputs into a structured circular decision. At this stage, the control architecture evaluates alternative short-loop options according to multi-dimensional criteria:

- Technical viability
- Economic cost
- Environmental impact
- Resource retention potential

Based on this evaluation, one of the following interventions is selected:

- Maintenance, when proactive intervention extends to the Middle-of-Life stage.
- Repair, when functional restoration prevents premature end-of-life transition.
- Remanufacturing, when full industrial recovery reintroduces the product or component into the Beginning-of-Life stage.

This gate represents the transformation of lifecycle intelligence into circular governance. The intervention decision is not reactive but informed by structured assessment and lifecycle-wide information continuity.

3.4.4. Feedback Integration and Adaptive Control An essential characteristic of the decision logic is its integration with the Feedback-to-Design Layer described in Section 3.2. Decisions executed at the End-of-Life stage generate structured insights regarding failure patterns, disassembly complexity, and recovery constraints.

These insights are systematically reintegrated into product design and process planning, enabling progressive optimisation of repairability, modularity, and remanufacturability (Mügge et al., 2024). Over time, the architecture control shifts from corrective circularity toward preventive lifecycle optimisation.

Thus, the operational decision logic is not linear but adaptive. Each intervention contributes to improving the informational and analytical basis of future decisions.

3.4.5. Implications of the Decision Logic The proposed operational logic demonstrates that short-loop circularity is not a binary capability, but a staged evaluation process governed by information depth and analytical maturity.

The Digital Value Chain becomes circularly effective when:

1. Lifecycle transparency eliminates information asymmetry.
2. Predictive modelling reduces technical uncertainty.
3. Structured decision governance selects optimal recovery pathways.
4. Feedback mechanisms enhance future product generations.

By formalising these gates, the framework transforms circularity from an end-of-life reaction into a lifecycle-regulated process.

3.5. Visual and Operational Representation

To enhance interpretability and practical applicability of the proposed framework, this subsection presents a structured tabular operationalisation and a visual representation of the Circular Control Architecture. These elements consolidate the hierarchical enablement levels and decision logic into an integrated model that can be applied analytically without requiring empirical specification.

Table 1. Operationalisation of Digital Circular Enablement Across the Manufacturing Lifecycle

Control Layer	Enablement Level	Core Question	Required Information/Capability	Circular Outcome
Data Acquisition	Informational Enablement	What is known about the product?	Product identity, configuration, material composition, lifecycle traceability	Circular feasibility established
State Estimation	Analytical Enablement	What is technically recoverable?	Remaining Useful Life estimation, degradation modelling, tolerance evaluation	Technically viable circular pathways identified
Circular Intervention	Decision Enablement	Which intervention maximises resource utility?	Multi-criteria evaluation (technical, economic, environmental)	Maintenance / Repair / Remanufacturing selected
Feedback-to-Design	Integrated Governance	How should future products improve recoverability?	Failure pattern analysis, disassembly insights, recovery constraints	Design-for-Circularity optimisation

Table 1 consolidates conceptual architecture into a structured decision-support logic, demonstrating how lifecycle information is progressively transformed into circular intervention and design optimisation.

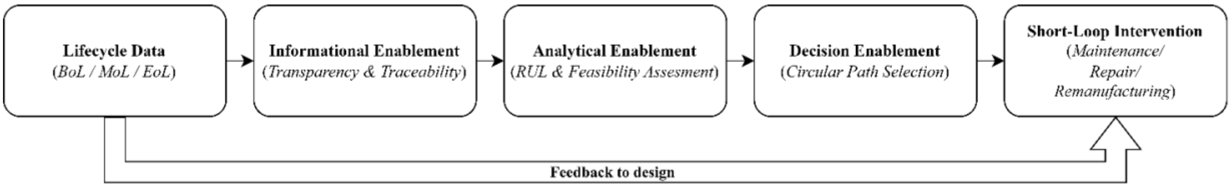

Figure 2. Circular Control Architecture of the Digital Value Chain

Figure 2 visualises the Digital Value Chain as a lifecycle-spanning control system rather than a linear sequence of technological applications. The layered structure illustrates how data acquisition enables state estimation, which in turn supports structured circular intervention. The feedback loop closes the control cycle by reintegrating recovery insights into future product design, thereby transforming circularity from reactive recovery into adaptive lifecycle governance. The figure also highlights the progression from data availability to decision execution, emphasising the role of hierarchical enablement levels in achieving circular governance.

4. Discussion

4.1. Reframing Digitalisation: From Technology Adoption to Control Architecture

Existing literature frequently approaches digital transformation in manufacturing through a technology-centric lens, focusing on individual tools such as Digital Twins, IoT systems, or data analytics platforms (Lăzăroiu et al., 2022). While these contributions demonstrate the technical feasibility of lifecycle monitoring and predictive maintenance, they often treat digital tools as isolated enablers rather than components of a systemic governance structure (Mügge et al., 2024).

The framework developed in this paper advances the discussion by reframing the Digital Value Chain as a circular control architecture. Instead of asking which technologies enable circularity, the proposed model addresses how lifecycle information is structured, interpreted, and operationalised across interconnected stages of the manufacturing value chain.

This distinction is critical. The effectiveness of short-loop circularity does not depend solely on the presence of sensing or modelling technologies, but on the degree to which these capabilities are integrated into a structured decision logic. By formalising the layered architecture and hierarchical enablement levels, this research shifts the focus from technological adoption to lifecycle governance.

4.2. Information Asymmetry as the Structural Barrier to Short-Loop Circularity

A central implication of the framework is that short-loop circularity is fundamentally constrained by information asymmetry rather than by recovery technology limitations (Z. Chen & Huang, 2021). Maintenance, repair, and remanufacturing require high-granularity knowledge of component condition, usage history, and degradation pathways.

When this knowledge is incomplete, recovery becomes economically uncertain and operationally risky. As a result, manufacturers default to conservative strategies, including material recycling or disposal.

The proposed control architecture demonstrates that:

- Informational enablement eliminates visibility gaps,
- Analytical enablement reduces technical uncertainty,
- Decision enablement structures intervention logic.

Short-loop circularity thus emerges as a function of digital enablement depth rather than as an isolated sustainability initiative.

4.3. Propositions for Digital Circular Governance

Based on the conceptual framework, the following propositions are derived:

1. **Proposition (P1)** The feasibility of short-loop circularity increases proportionally with lifecycle-wide informational transparency. This proposition implies that manufacturing systems lacking traceable product identity and usage history are structurally limited in their ability to implement repair and remanufacturing strategies.
2. **Proposition (P2)** Predictive state estimation capabilities reduce recovery uncertainty and increase the likelihood of high-value circular interventions. Where predictive modelling and degradation assessment are integrated, decision-makers can proactively select maintenance or remanufacturing rather than defaulting to end-of-life disposal.
3. **Proposition (P3)** Structured decision enablement is required to translate lifecycle intelligence into consistent circular action. Without a governance mechanism linking analysis to intervention, digital insight remains operationally underutilised.
4. **Proposition (P4)** Closed-loop feedback integration enhances long-term circular performance by embedding recovery insights into future product design. This proposition suggests that circularity becomes progressively more efficient when recovery data informs modularity, standardisation, and reparability at the design stage.

4.4. Theoretical Advancement

The primary theoretical contribution of this study lies in formalising digital circularity as a control problem rather than a technology implementation challenge.

While prior research has highlighted the enabling role of Digital Twins and IoT systems, the present framework integrates these capabilities into a lifecycle-spanning control architecture. This architecture clarifies how data acquisition, state estimation, and decision governance operate sequentially to regulate circular intervention.

By introducing hierarchical enablement levels and structured feasibility gates, the framework provides a replicable reasoning structure for evaluating digital-circular maturity. It also bridges manufacturing systems theory and circular economy literature by situating circularity within a governance-oriented digital infrastructure.

Building upon the proposed framework, this study contributes to the literature in three specific ways.

First, it conceptualises the Digital Value Chain not as a collection of enabling technologies, but as a lifecycle-wide circular control architecture. This shifts the perspective from technology adoption toward structured governance of circular processes.

Second, it introduces hierarchical levels of digital circular enablement, providing a novel explanation of how lifecycle data is progressively transformed into circular action. This contribution offers a structured lens for analysing the maturity of digital-circular integration in manufacturing systems.

Third, it formalises short-loop circularity as an operational decision process through feasibility gates, linking informational availability, technical feasibility, and intervention selection. This provides a reproducible logic for understanding how circular decisions can be systematically governed across the product lifecycle.

Together, these contributions extend existing research on digital manufacturing and circular economy by integrating technological capabilities into a coherent lifecycle-oriented control framework.

This positions the Digital Value Chain not only as a technological enabler, but as a theoretical construct that integrates value chain theory, information asymmetry, and cyber-physical systems into a unified circular governance model.

4.5. Managerial Implications

For manufacturing enterprises, the framework suggests that circularity cannot be achieved through isolated pilot projects or singular technology deployments. Instead, firms must:

- Ensure lifecycle data continuity,
- Integrate predictive modelling into operational processes,
- Establish structured circular decision protocols,
- Institutionalise feedback-to-design mechanisms.

Investments in digitalisation should therefore be evaluated not solely on efficiency gains but on their capacity to enable lifecycle-wide circular governance.

5. Conclusions and Future Research

This paper conceptualised the Digital Value Chain (DVC) as a circular control architecture that systematically enables short-loop circularity in manufacturing systems. Rather than framing digitalisation as a collection of isolated technologies, the study positioned it as a lifecycle-wide governance infrastructure regulating data acquisition, state estimation, circular intervention, and feedback-to-design processes.

The central contribution of this research lies in three interrelated elements:

1. The formalisation of the Digital Value Chain as a multi-layered circular control architecture.
2. The introduction of hierarchical levels of digital circular enablement—informational, analytical, and decision.
3. The development of an operational decision logic structured around feasibility gates governing maintenance, repair, and remanufacturing.

By reframing circularity as an information-governed control problem, this paper advances the understanding of why short-loop strategies often remain underutilised despite technological feasibility. The findings suggest that circular performance is determined less by recovery capability and more by lifecycle-wide integration of data, predictive modelling, and structured decision governance.

The proposed framework contributes to both circular economy theory and digital manufacturing research by bridging the gap between technology adoption narratives and systemic lifecycle regulation. It provides a conceptual foundation for assessing digital-circular maturity and for guiding future empirical validation.

5.1. Limitations

This study is subject to several limitations inherent to conceptual research.

First, the proposed framework is derived through literature-based abstraction and therefore reflects a generalised conceptual perspective rather than sector-specific conditions. The applicability of the model may vary across different industrial contexts depending on the level of digital maturity and lifecycle integration.

Second, the framework is based on selected streams of literature focusing on digital manufacturing and circular economy. While the review captures recurring patterns and conceptual relationships, it does not aim to provide exhaustive coverage of all relevant studies.

Third, the proposed model represents a technology-neutral conceptual architecture. As such, it does not account for implementation-specific constraints such as organisational structure, data ownership, or interoperability challenges across supply chain actors.

Future research is therefore required to empirically test and validate the applicability of the framework in real-world manufacturing environments and to assess its generalisability across sectors. These limitations define the scope of the framework and provide direction for future empirical and methodological extensions.

5.2. Future Research Directions

Future research may extend this work in several directions:

1. **Empirical Validation:** Testing the proposed control architecture in sector-specific case studies (e.g., automotive, industrial equipment, electronics) to evaluate its practical applicability.
2. **Quantitative Modelling:** Developing simulation-based or agent-based models to assess how varying levels of digital enablement influence circular performance indicators.
3. **Digital Governance and Data Ownership:** Investigating organisational and contractual barriers to lifecycle data integration across supply chain actors.
4. **Circular Maturity Assessment Frameworks:** Translating the hierarchical enablement levels into measurable maturity indices for benchmarking manufacturing systems.

In conclusion, this study demonstrates that short-loop circularity is fundamentally an information-dependent process. The Digital Value Chain, when conceptualised as a lifecycle-wide control architecture, provides the structural conditions necessary for transforming fragmented recovery actions into coordinated, adaptive, and value-preserving circular governance within manufacturing systems. This implies that firms should assess digital investments not only in terms of efficiency gains, but also in their contribution to lifecycle-wide circular governance capabilities.

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Declarations

Competing Interests The authors declare no competing interests.

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