Industry 4.0 Information Systems for Materials Circularity in Supply Chains: Industry Issues and Research Directions

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Abstract: The purpose of this paper is to explore the role of information systems in manufacturing to support material circularity practices in the supply chain. The paper attempts to study the usefulness of manufacturing operations management (MOM) systems, particularly manufacturing execution systems (MES), in enabling traceability and supply chain integration for tracking product material details. Theoretical propositions made on MOM systems for materials circularity (based on the literature study) were empirically examined using needs assessment from two case companies with complex product material requirements. Based on the qualitative analysis of propositions and empirical findings, the paper identified traceability-enabled methods, supply chain integration, and the adoption of Industry 4.0 technologies as potential enablers for achieving materials circularity goals. As a result, the priorities for developing research agenda in this area to design factories of the future and to achieve Industry 4.0 vision that supports circular economy were established. Future research directions are put forward and future work will include an in-depth case study analysis to explore the role of Industry 4.0-compliant MOM systems to meet evolving regulatory demands and operational scalability across the supply chain.

1 INTRODUCTION

Materials Circularity in Manufacturing: One of the biggest challenges manufacturing companies worldwide currently face is adapting to evolving sustainability compliance requirements while tailoring their manufacturing operations and equipment. For example, a global electronics manufacturer may need to comply with stricter regulations on carbon emissions and waste management while simultaneously implementing advanced automation and Industry 4.0 technologies. This could involve retrofitting production lines with energy-efficient equipment and materials recycling in the factory.

The concept of material circularity covers a much broader scope with implications for supply chains, necessitating changes across all aspects of the supply chain. It requires the adoption of modern equipment, particularly advanced enterprise information systems, to achieve sustainability goals. However, this transition remains a work in progress within the manufacturing industry and demands research attention to address existing knowledge gaps and industrial challenges.

The circular economy (CE), as highlighted by the European Commission (EU) (European Union, 2015), calls for a lifecycle approach. However, its core principle in practice focuses on increasing material circularity by converting materials at the end of their service life into resources for new applications (European Union, 2015).

Materials circularity in manufacturing refers to the concept of creating a closed-loop system for materials, where resources are used efficiently, waste is minimized, and materials are continually recycled and reused in the production process. This approach aims to reduce the environmental impact of manufacturing activities by promoting sustainability

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and minimizing the depletion of natural resources (Dumée, 2022).

Many manufacturing companies globally are adjusting their manufacturing systems and practices to meet future regulations of circular economy. Some of the practices of materials circularity in manufacturing include: Recycling and Reuse, Waste reduction, Design for sustainability, Remanufacturing, and Materials traceability.

EU and International Policies Associated With Materials Circularity: several EU and international policies are associated with the concept of circular economy, which include materials circularity. Some of these are https://commission.europa.eu/index_en:

- Circular Economy Action Plan (CEAP): The CEAP is an EU initiative that presents strategies and actions to promote a circular economy. It covers product design, waste management, recycling targets, and measures to reduce the environmental impact of products.
- Waste Framework Directive: It establishes the legislative framework for waste management in the EU. It sets out key principles, including waste hierarchy, extended producer responsibility, and recycling targets.
- Directive on single-use plastics: This directive aims to reduce the impact of certain plastic products on the environment, including bans or restrictions on single-use plastic items and promotion of circular design.
- Ecodesign Directive: This sets requirements for the environmental performance of energy-related products, promoting circularity by encouraging longer product lifetimes, easier repairability, and recyclability.
- Plastics Strategy: The EU Plastics Strategy focuses on improving the economics and quality of plastics recycling, reducing single-use plastics, and promoting eco-friendly alternatives.

Several international policies support the circular economy with implications for manufacturing. The United Nations (UN) Sustainable Development Goals, particularly Responsible Consumption and Production, emphasize sustainable practices. The Basel Convention regulates hazardous waste movements and management, while the Paris Agreement indirectly promotes circular principles through resource efficiency. The UN Environment Programme advances initiatives on sustainable consumption, and the OECD provides guidelines for circular economy strategies for member countries.

Regulations and recommendations from various governing bodies make it evident that stricter rules for manufacturing are on the horizon, and manufacturers must quickly adapt to these growing challenges. However, many brownfield manufacturing enterprises continue to rely on traditional manufacturing methods and legacy equipment, which hinder their ability to meet these evolving requirements.

While many studies highlight the importance of information systems in manufacturing supply chains to achieve circular economy goals (Awan et al., 2021) (Chhimwal et al., 2022), the roadmap for their implementation remains unclear. Exisiting literature highlights Industry 4.0 as an enabler of circular supply chains (Gebhardt et al., 2022; Taddei et al., 2022). (Zeiss et al., 2021) mention that product design for reuse addresses repairability and upgradeability, where digital processes and flexible platforms enable design, analysis, and collaboration by facilitating disassembly and reuse. They highlight Industry 4.0 technologies, such as the Internet of Things, Big Data Analytics, and cloud computing, as beneficial for circular supply chains.

Traditionally, enterprise information systems in manufacturing were designed to enhance operational efficiency, leaving their potential role in supporting circular economy objectives underexplored. There are limited studies in this area in manufacturing. This demands further inquiry into the future operational needs of factories and supply chains to use information systems accordingly.

Motivated by this need, this paper examines how manufacturing companies are adapting to these regulations and identifies which factory information systems have the potential to address these challenges in supply chains—a question that has not been widely studied in the existing literature.

Section 2 introduces the theoretical framing to the research, Section 3 describes the approach, followed by an analysis of company case study narratives in Section 4. Section 5 concludes the position and presents the future work.

2 MANUFACTURING INFORMATION SYSTEMS FOR MATERIALS CIRCULARITY

Enterprise information systems in manufacturing, such as enterprise resource planning (ERP) and

MES/MOM play a crucial role in promoting materials circularity within the context of a circular economy. These systems help manage and optimize the flow of materials through various stages, from production to consumption and recycling.

In Industry 4.0, these systems leverage technologies such as Internet of Things (IoT) sensors visibility and traceability of materials, which are essential for supporting recycling, reuse, and remanufacturing processes. ERP systems can integrate data from various functions and are capable of monitoring material usage. MES/MOM can provide almost real-time product centric data for decision-making on material recovery, reuse and remanufacturing processes. Product Lifecycle Management (PLM) systems can document the environmental impact of materials and products, helping manufacturers design for circularity.

A proven example of traceability is of RFID tags in the automotive industry to track the recycling of vehicle parts. By using such tracking capabilities, companies can ensure that materials such as metals, plastics, and composites are recovered and reused rather than discarded.

Requirements of future factories: Given the regulations outlined in Section 1, numerous accountability and reporting issues arise. With the changing regulations, manufacturers need to rethink their computer-based information systems and use advanced manufacturing operation management systems to address these issues. A study (Omair et al., 2024) suggested that manufacturing information systems for materials circularity, in the context of recycled plastic (RP), face challenges due to the high variability in quality, composition, properties, and lead time of RP. These variations create uncertainty in material requirement planning, making it difficult to optimize quantities and reorder times (Omair et al., 2024).

Future factories will also require advanced Internet of Things (IoT) capabilities to optimize operations through real-time monitoring, tracking, and control, enabling efficient use, extended product lifecycles, and increased resource utilization for circular economy (Uhrenholt et al., 2023). This is in line with the Industry 4.0 vision of data-driven decision-making, supported by predictive and prescriptive analytics. MES/MOM, being a factory database and a manufacturing cockpit is well positioned to integrate with Industrial IoT to support the transition towards material circularity in manufacturing supply chains.

Figure 1 presents the MES/MOM position in the manufacturing information systems.

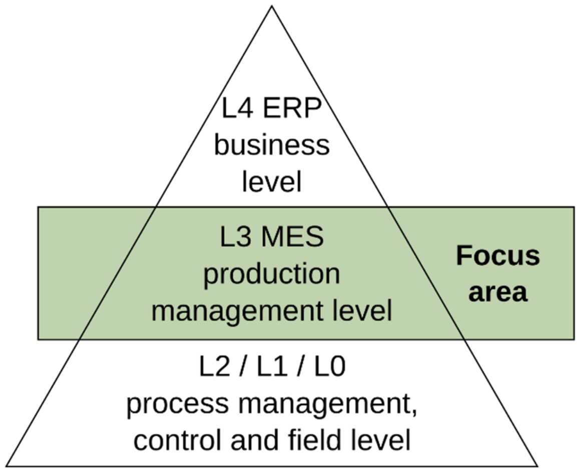

Figure 1: ISA 95 Levels of functional hierarchy in a manufacturing enterprise. (Scholten, 2007)

3 METHODOLOGY

We used a combination of selective literature review and case study approach to explore the role of MOM systems in enabling materials circularity practices. This methodology combines theoretical development with empirical exploration to identify key research gaps. First, we explored theoretical background based on selective literature review on the topics 'manufacturing information systems', 'materials circularity', 'circular supply chains' and 'manufacturing operations management'. We prioritized recent studies from 2018-2025. The review results highlighted a gap in literature on integration of MOM systems with Industry 4.0 technologies to enhance traceability for materials circularity. These literature findings were supported by the subsequent empirical analysis.

To explore this gap, we used an in-depth exploratory case study approach, drawing on established methodologies by Voss (2002) (Voss, 2010) and (Yin, 2014). The study focused on two large global manufacturing companies, anonymized as Company A and Company B for confidentiality. Both companies operate at scale with complex material requirements in their production processes. The case study methodology followed the six-stage framework proposed by (Flynn et al., 1990). Data collection included field visits involving direct observations and discussions with manufacturing personnel, supply chain managers, and sustainability officers. We also reviewed publicly available company reports, operational manuals, and regulatory compliance records. To contextualize and triangulate the data, we integrated insights from the existing literature.

To ensure validity, we applied a theoretical replication strategy, using Company B to confirm findings and explore variations in materials circularity needs under different operational contexts. Reliability was maintained through data triangulation, combining insights from literature, field visits, and archival documentation. Preliminary case study analysis contributed to the development of hypotheses regarding the role of MOM systems in achieving materials circularity goals.

This approach helped us in presenting the case study findings in Section 4.

4 ANALYSIS AND FINDINGS

In this section, we present two exemplar case study narratives of companies on their material circularity journeys. These international companies have a large manufacturing footprint and are industry leaders in their respective sectors, known for their iconic products.

Case 1 – High end Plastic Consumer Goods: A global leader in plastic consumer goods manufacturing, this company boasts an iconic product and nearly a century of industry presence. With a widespread manufacturing network spanning five sites across three continents, it has adaptable supply chains and an e-commerce platform to cater to the global demand for personalized products. Company A offers over 3,000 distinct shapes of components in a wide range of configurations which are durable for a long functional lifetime and often passed on into secondary market. In terms of reuse/recycling this also means that many generations of material composition can be found in active market use, some of which also contain substances that do not live up to current requirements. This introduces a challenge in terms of sorting products when they return through take back programs so that unwanted substances are not mixed into the material pool.

Company A has for 20 years been actively engaged in changing the composition of its materials platform and is under increasing internal and external pressure to adopt sustainable practices, particularly in terms of reducing plastic waste and improving product recyclability.

In the 2010s, Company A integrated a new comprehensive PLM system into its enterprise platform to accelerate product launches and enhance master data management across its supply chain. This integration has driven increased automation in product launches, production planning, control, and lifecycle management, resulting in a notable improvement in product output through more granular control over materials, production processes, and product flows. The upgraded data systems have provided deeper insights into costs and manufacturing structures, facilitating more informed decision-making. A recent initiative focuses on experimenting with dynamic recipes to align material composition, process parameters, and advanced customer requirements. Initially aimed at boosting process control and optimization, this program, as it evolves, will enable more significant changes in material composition, processes, and customization. These changes, whether process optimizations or new elements, often require extensive testing and validation, but digital twins within the industrial metaverse now serve as a central hub to integrate operational systems into a unified virtual environment. For example, recipe adjustments can be simulated and automatically updated across connected systems.

Case 2 – Pharmaceuticals and Health Care (Packaging): Company B is a global leader in the pharmaceutical industry, known for its commitment to fighting chronic diseases by advancing innovative medicines and delivery systems. It is a well-established company operating a vast network of manufacturing sites across multiple continents. Company B is also known for its pioneering work in medicine delivery systems, where it has a self-reported plastic footprint of 0.35kg per patient despite concerted efforts to reduce consumption by, among other things, introducing reusable delivery systems.

Company B faces the challenge of recycling its plastic medical devices while adhering to stringent health and safety regulations, which means that closed loop solutions are not possible under current circumstances, complicating efforts to improve product recyclability and reduce plastic waste. Compared to Company A, ensuring the right functional properties of the material is not sufficient for Company B as the documentation trail also need to comply with regulatory regimes in the market.

Recycled materials often exhibit inconsistent properties, such as variability in composition, contamination risks, and reduced mechanical integrity, which can compromise product safety and sterility. Regulatory frameworks, including Food and Drug Administration (FDA) and EU guidelines, require traceability and compliance, complicating the use of recycled plastics. Additionally, the compatibility of recycled plastics with sensitive pharmaceutical products, such as drugs and medical devices, remains uncertain. Ensuring uniformity, maintaining compliance, and addressing consumer safety concerns demand advanced sorting, cleaning, and testing technologies, which increase costs and complicate adoption. The company has implemented a take-back program for packaging and dispensing devices, connecting it to a recycling network for high-value repurposing. While legislation and regulations currently prevent the company from reusing materials internally, it is progressing towards closed-loop recycling, supported by material verification and detailed process tracking to meet regulatory requirements for materials not directly in contact with active ingredients.

We analyze the empirical data from the two companies and triangulate it with archival documents and industry reports. This data is used to identify specific requirements and challenges, which are summarized in Table 1.

Table 1: Summary of collected qualitative data.

Source	**Primary data from Company A**	**Primary data from Company B** *(to ensure reliability)*
Size (employees)	>10,000	>10,000
Industry	High end plastic consumer goods	Pharmaceuticals
Field study	Denmark	Denmark
Finding 1 Context	**Dynamic recipes (mixability, additives, compounding)**	**Complying with industry standards and regulation** (e.g., FDA)
Finding 2 Aim	Recycled content in core product, increased customization, and process control for optimization	Recycled content in primary and secondary packaging
Finding 3 Problem	Meeting high level functional demands of products	Documentation trail to meeting high standards and demand from regulatory bodies

Both companies face significant challenges in adapting to changing regulatory requirements. This highlights the need for advanced information systems in supporting circularity via data visibility. We argue that MES/MOM has the potential to address these issues through dynamic recipes. Dynamic recipes refer to production instructions or formulations that adjust based on variables such as material quality, equipment conditions, or batch requirements. MES/MOM can handle this by dynamically updating work instructions, equipment settings, and quality checks during production.

MES/MOM Functionalities Supporting Circular Economy:

- MES/MOM supports dynamic recipes through ongoing alignment of material characteristics, machine settings, and market demands. MES/MOM manages and executes production orders on the shop floor, often interfacing with real-time data from equipment and sensors.
- It supports the real-time alignment of actual circumstances in production and the material usage by recording the production data in real-time.
- It enables material documentation and maintains verified material histories by documenting material properties and minimizing the need for additional material testing.
- It ensures traceability and compliance by recording recipe changes and their impact on the final product.

In Figure 2, we present the functionality diagram of MES/MOM and highlight the functionalities that could address the materials circularity issues in manufacturing supply chains through its integration with other enterprise systems and information visibility.

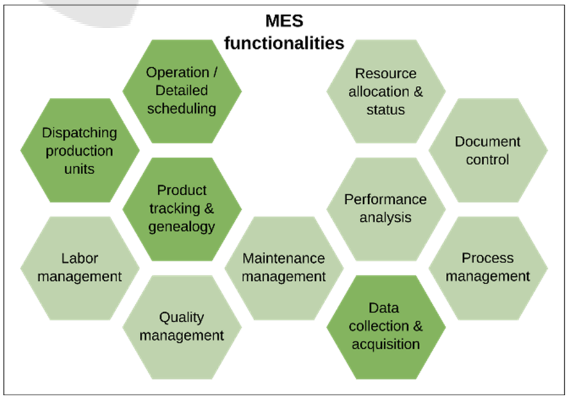

Figure 2: 11 functionalities of MES/MOM according to (MESA INTERNATIONAL – WHITE PAPER NUMBER 2, 1997)

5 CONCLUSIONS & FUTURE RESEARCH DIRECTIONS

Our study explored how manufacturing operations management (MOM) systems could enhance traceability across the supply chain to support materials circularity practices in manufacturing. By analyzing the aims and processes of our case companies, we identified the relevance of MOM functionalities, such as **dynamic recipes**, which allow production processes to adapt to varying inputs or conditions. While traditionally utilized in the process industry, dynamic recipes highlight the potential of MOM systems to support materials circularity across diverse manufacturing sectors. Furthermore, the integration capabilities of MOM systems with other enterprise systems, such as enterprise resource planning (ERP) and product lifecycle management (PLM), provide opportunities to align production practices with material circularity principles.

The key contributions of this paper include:

- We provided a perspective on conducting high-impact research for complex manufacturing supply chains to meet evolving regulatory demands. MOM systems were shown to effectively track material flows, enabling manufacturing personnel to monitor product lifecycle details and improve recycling and reuse rates. Recognizing the socio-technical and organizational aspects of information systems, we advocate for future research to explore MES/MOM usability and their benefits in supporting circular economy principles.
- **Potential in MES/MOM**: We highlight the need for Industrial IoT-based traceability. Future research on this topic should focus on the integration of IIoT-enabled traceability within MOM systems to better align with regulatory requirements and sustainability targets, particularly in international manufacturing networks.
- The study highlights the limited attention in existing literature regarding MES/MOM benefit realization for scalable solutions to achieve material circularity goals. This paper contributes by emphasizing the need for further exploration in this area.
- **Establishing a research agenda**: A concept was developed to guide future research, suggesting that the integration of information systems, especially Industry 4.0 compliant MES/MOM in manufacturing operations can significantly improve supply chain visibility and facilitate compliance with circular economy principles.

As far as we know, this is the first study to combine the topic of MES/MOM with material circularity solutions in manufacturing. Most studies on Industry 4.0 for circular supply chains focus on IoT and AI but overlook enterprise information systems like MES/MOM. Future research should explore how these systems can support business models such as Product-as-a-Service and take-back schemes alongside Industry 4.0 adoption. This study contributes to directives like the EU Green Deal and the UK's Net Zero goals.

Our position within the context of Industry 4.0 principles highlights the key capabilities of MOM systems, such as real-time adjustments, traceability, and interconnection, as enablers of circular economy practices. As extended producer responsibility policies tighten, manufacturers need real-time material traceability. While MES/MOM can facilitate this, challenges remain, including integration with legacy systems, data standardization, cybersecurity risks, and high AI implementation costs, highlighting the need for further research on enabling technologies.

Future work will include in-depth case studies to explore how leveraging MOM systems for materials circularity can be most effective when supported by robust supply chain partnerships and real-time data sharing. This ongoing research aims to deepen understanding and provide actionable insights for designing sustainable manufacturing operations aligned with Industry 4.0 and circular economy goals.

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