Drivers and Barriers to Reconfigurable Manufacturing Systems (RMS) Adoption in Industry 4.0: A Systematic Review

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Abstract

The emergence of Industry 4.0 has significantly transformed manufacturing systems by integrating advanced digital technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), and cyber-physical systems. Reconfigurable Manufacturing Systems (RMS) have emerged as a promising solution to address the limitations of traditional manufacturing systems by offering scalability, modularity, and customized flexibility. This review paper aims to systematically analyze the key drivers and barriers influencing the adoption of RMS in Industry 4.0 environments. The study synthesizes existing literature to identify technological, economic, and organizational factors affecting RMS implementation. Furthermore, it highlights research gaps and proposes a conceptual framework to guide future research and industrial application. The findings indicate that while technological advancements and market demand act as major drivers, challenges such as high initial investment, lack of skilled workforce, and integration issues hinder widespread adoption. This review contributes to both academia and industry by providing a structured understanding of RMS adoption dynamics.

Keywords: Reconfigurable Manufacturing System, Industry 4.0, Drivers, Barriers, Smart Manufacturing, ISM, MICMAC

1. Introduction

The manufacturing sector is undergoing a profound transformation driven by the emergence of **Industry 4.0**, often referred to as the Fourth Industrial Revolution. This paradigm integrates advanced technologies such as cyber-physical systems, the Internet of Things (IoT), artificial intelligence, and big data analytics to enable smart, autonomous, and interconnected production environments (**Kagermann et al., 2013; Lasi et al., 2014; Lee et al., 2015**). The objective of Industry 4.0 is to achieve highly flexible, efficient, and customized manufacturing systems capable of responding dynamically to changing market demands.In this context, **Reconfigurable Manufacturing Systems (RMS)** have emerged as a critical enabler of Industry 4.0. RMS are designed to rapidly adjust their structure, hardware, and software to modify production capacity and functionality in response to fluctuations in product demand or design changes (**Koren et al., 1999; Koren & Shpitalni, 2010**). Unlike traditional dedicated manufacturing systems, which lack flexibility, or flexible manufacturing systems (FMS), which may be costly and overly generalized, RMS provide a balanced solution by offering customized flexibility, scalability, and rapid adaptability.The increasing need for mass customization, shorter product life cycles, and volatile market conditions has intensified the adoption of RMS in modern industries (**ElMaraghy, 2005; Mehrabi et al., 2000**). The integration of RMS with Industry 4.0 technologies enhances operational agility, improves product quality, reduces lead time, and supports sustainable manufacturing practices (**Bortolini et al., 2017; Ivanov et al., 2016**). Furthermore, RMS enables modularity, integrability, convertibility, diagnosability, and scalability—key characteristics required for smart manufacturing systems (**Koren & Shpitalni, 2010**).Despite these advantages, the adoption of RMS within Industry 4.0 is not without challenges. Organizations face several **drivers** such as technological advancement, competitive pressure, and demand for customization, alongside **barriers** including high initial investment, system complexity, lack of standardization, and workforce skill gaps (**Mourtzis et al., 2016; Sony & Naik, 2019**). Additionally, integrating legacy systems with modern digital technologies poses significant technical and organizational difficulties.A growing body of literature has explored various aspects of RMS, including design methodologies, system architectures, and implementation strategies. However, there remains a need for a comprehensive synthesis of the key drivers and barriers influencing RMS adoption within the Industry 4.0 framework. Previous studies have emphasized the strong linkage between RMS and Industry 4.0 technologies while identifying gaps between theoretical developments and industrial applications (**Brettel et al., 2014; Zhong et al., 2017**).Therefore, this study aims to present a **systematic review of the drivers and barriers to RMS adoption in Industry 4.0**, providing insights into current trends, challenges, and future research directions. By synthesizing existing literature, this paper contributes to both academic research and industrial practice by supporting informed decision-making for successful RMS implementation.

2. Literature Review

The concept of advanced manufacturing has undergone a paradigm shift with the emergence of Industry 4.0, which emphasizes digitalization, automation, and intelligent decision-making across production systems. Originally introduced as part of Germany's high-tech industrial strategy, Industry 4.0 represents a transformation driven by interconnected technologies that enable real-time communication between machines, systems, and humans. Scholars such as Kagermann et al. (2013) and Lasi et al. (2014) describe Industry 4.0 as a cyber-integrated production paradigm characterized by interoperability, decentralization, and real-time data exchange. Further studies by Lu (2017) and Zhou et al. (2015) highlight that these features enable the realization of smart factories, where systems are capable of autonomous decision-making and continuous optimization. Additionally, enabling technologies such as the Internet of Things (Atzori et al., 2010), Cyber-Physical Systems (Lee et al., 2015), artificial intelligence (Jordan & Mitchell, 2015), big data analytics (Wang et al., 2016), and cloud computing (Xu et al., 2018) play a crucial role in enhancing predictive maintenance, operational efficiency, and supply chain integration (Ivanov et al., 2016).Parallel to these developments, the concept of Reconfigurable Manufacturing Systems has emerged as a strategic solution to overcome the limitations of traditional manufacturing systems. Introduced by Koren et al. (1999), RMS focuses on providing customized flexibility and rapid adaptability within a specific product family. Unlike conventional manufacturing systems, RMS is designed based on modular architectures that allow system components to be easily added, removed, or modified. Mehrabi et al. (2000) emphasized that modularity and integrability enable seamless system adjustments, while Koren and Shpitalni (2010) highlighted scalability and convertibility as essential features that allow manufacturers to respond effectively to fluctuating market demands. These characteristics collectively enhance system responsiveness, reduce downtime, and improve production efficiency, making RMS a key enabler of modern manufacturing systems.Manufacturing flexibility and responsiveness have become critical performance indicators in the era of dynamic markets and mass customization. RMS significantly contributes to these capabilities by enabling rapid reconfiguration of production systems. Koren et al. (1999) demonstrated that RMS provides product-specific flexibility, while Mehrabi et al. (2000) argued that its modular structure allows quick system adjustments with minimal disruption. Furthermore, ElMaraghy (2005) emphasized that RMS is highly effective in managing uncertainties such as demand variability and product diversification. As a result, RMS enhances production flexibility, improves responsiveness, and enables manufacturers to align their operations with rapidly changing market conditions.In addition to internal manufacturing improvements, Industry 4.0 has significantly transformed supply chain management through digital integration and real-time data exchange. Ivanov et al. (2016) reported that Industry 4.0 technologies enhance supply chain visibility and coordination, enabling better synchronization across different stages of production and distribution. Similarly, Kamble et al. (2018) found that digital transformation improves decision-making capabilities, reduces lead times, and enhances overall operational efficiency. The integration of advanced technologies facilitates real-time tracking, accurate forecasting, and improved resilience against disruptions, thereby strengthening the overall supply chain performance.Recent studies have increasingly emphasized the integration of RMS with Industry 4.0 technologies to develop intelligent and adaptive manufacturing systems. Zhong et al. (2017) highlighted that smart manufacturing systems combine the structural flexibility of RMS with the digital intelligence of Industry 4.0 to achieve superior performance. Lee et al. (2015) further demonstrated that cyber-physical systems enable real-time monitoring, control, and optimization of manufacturing processes, thereby enhancing the capabilities of RMS. This integration leads to improved production planning, higher system efficiency, and the development of intelligent manufacturing environments where systems can self-adapt and optimize based on real-time data.The adoption of RMS within Industry 4.0 environments is driven by a combination of technological, economic, market, and organizational factors. Technological drivers include advancements in IoT, CPS, and artificial intelligence, which enable seamless system integration and automation (Lee et al., 2015). Market drivers such as increasing demand for mass customization (Pine, 1993) and rising competitive pressure (Kamble et al., 2018) encourage organizations to adopt flexible manufacturing systems. Economic factors, including cost efficiency and productivity improvement, further support adoption, while organizational drivers such as government policies and digital transformation initiatives play a crucial role in facilitating implementation. These drivers collectively enhance manufacturing competitiveness and operational efficiency.Despite its numerous advantages, the adoption of RMS in Industry 4.0 contexts faces several challenges. Ghobakhloo (2020) identified high initial investment costs as a major barrier, particularly for small and medium enterprises. Additionally, the lack of skilled workforce and difficulties in integrating RMS with legacy systems pose significant challenges (Kamble et al., 2018). Cybersecurity risks associated with digital technologies (Lee et al., 2015) and resistance to organizational change further complicate implementation. These barriers are more pronounced in developing economies, where technological infrastructure and expertise may be limited, thus hindering the widespread adoption of advanced manufacturing systems.

A critical review of the literature reveals several research gaps in the domain of RMS and Industry 4.0 integration. Most studies have examined these concepts independently, with limited focus on their combined application. Furthermore, there is a lack of structured analytical frameworks for evaluating drivers and barriers, and minimal use of methodologies such as ISM, MICMAC, and DEMATEL. Empirical validation of proposed models is also insufficient, and there is limited consideration of the combined impact of technological, economic, and organizational factors. These gaps highlight the need for comprehensive and integrated research approaches to better understand and facilitate RMS adoption in Industry 4.0 environments.

Table 1: Summary of Literature on RMS and Industry 4.0

Author(s) & Year	**Focus**	**Methodology**	**Key Findings**	**Research Gap**
Kagermann et al. (	Industr concep	Conceptual stud	Introduced Industry 4.0 as digital transformation str for manufacturing	Lack of implementation frameworks
Lasi et al. (2014)	Industr charac s	Review	Defined key features such interoperability and decentralization	Limited practical validation
Zhou et al. (2015)	Smart manuf g	Analytical study	Highlighted importance o real-time data and automa	Integration challenges not addressed
Lee et al. (2015)	Cyber- al Syst	Conceptual fram	CPS enables real-time monitoring and intelligent control	Limited application in RMS
Atzori et al. (2010	Interne Things	Survey	IoT enables connectivity communication between d	Security and scalability issues
Wang et al. (2016)	Big Da manuf g	Review	Big data improves predict maintenance and efficienc	Lack of integration with RMS
Koren et al. (1999	RMS c	Theoretical stud	Introduced RMS with mo and scalable design	Early-stage concept, lacks digital integration
Mehrabi et al. (20	RMS charac s	Review	Identified modularity, sca integrability	No Industry 4.0 linkage
Koren & Shpitalni (2010)	RMS c	Analytical study	RMS improves responsiv and productivity	Limited real-world case studies
ElMaraghy (2005)	Flexibl manuf g	Review	RMS enhances adaptabili system responsiveness	No digital integration focus

Ivanov et al. (201	Supply in Indu 4.0	Analytical study	Digital technologies impr supply chain resilience	RMS integration not explored
Kamble et al. (201	Industr adopti	Empirical study	Identified drivers like technology and competiti	Limited focus on RMS
Ghobakhloo (202	Industr barrier	Review	High cost and skill gap ar challenges	Lack of RMS-specific analysis
Zhong et al. (2017	Smart manuf g syste	Review	Integration of digital technologies improves eff	Limited RMS application
Morgan et al. (202	Smart (SR*)	Comprehensive	RMS evolving into intelli distributed systems with integration	Need for structured adoption models
Bortolini et al. (20	RMS researc trends	Literature review	Identified need for perfor metrics and industrial ado	Lack of empirical validation
Yelles-Chaouche (2020)	RMS optimi	Review	Focused on cost, time, an production optimization	Limited Industry 4.0 integration
Andersen et al. (2	RMS metho	Case-based stud	Proposed structured RMS approach	Difficult industrial application
Li et al. (2024)	Smart Recon le Manuf g	NLP-based litera analysis	Identified convergence of and smart manufacturing paradigms	Lack of real-world validation (ScienceDirect)
Arnarson et al. (20	Intellig RMS archite	Conceptual fram	Proposed autonomous reconfigurable system wit integration	Implementation complexity remains high (ScienceDirect)
Milisavljevic-Sye (2024)	Sustai RMS	Analytical study	RMS enhances adaptabili sustainability in productio	Limited Industry 4.0 integration focus (Taylor & F Online)
Patel et al. (2025)	Industr adopti challe	Review	Identified cybersecurity, interoperability, and cost i	Need for integrated RMS framework (STM Journa
Haller et al. (2025	Industr produc system	Systematic revie	Categorized manufacturin systems based on digital maturity	RMS-specific classification lacking (Springer)
Ramu (2024)	Industr impact	Review	Digital technologies impr productivity and efficienc	Limited focus on RMS integration (AnaPub)

Windmann et al. (	AI integra Industr	Review	Identified data, workforce system integration challen	RMS adoption not explicitly studied (arXiv)
Tordeux et al. (20	Reliab Industr	Review	AI and IoT improve predi maintenance and system reliability	Complexity and data management issues (arXiv)
Lee & Su (2023)	AI & knowl models	Conceptual	Proposed industrial know model for smart manufact	Lack of RMS application (arXiv)
World Scientific (	RMS + Industr integra	Review	Integration improves agili quality, and cost efficienc	Implementation barriers remain significant (World Scientific)

Table 2: Thematic Literature Review (Drivers – Barriers – Technologies in RMS & Industry 4.0)

Author(s) &	**Theme**	**Focus Area**	**Methodology**	**Key Findings**	**Research Gap**
Kagermann et a (2013)	Drivers	Industry 4.0 strate	Conceptual	Digital transformat improves competiti	Lack of implementation mo
Lasi et al. (201	Technologies	Industry 4.0 characteristics	Review	Identified interoper and decentralizatio	Limited empirical validatio
Lee et al. (2015	Technologies	Cyber-Physical S	Conceptual	CPS enables real-ti monitoring and con	Integration with RMS limite
Atzori et al. (20	Technologies	Internet of Things	Survey	IoT enables connec and smart systems	Security challenges
Koren et al. (19	Drivers	RMS concept	Theoretical	Introduced modula scalable systems	No digital integration
Mehrabi et al. (	Technologies	RMS characterist	Review	Modularity, scalabi convertibility ident	Limited Industry 4.0 link
Kamble et al. (	Drivers	Industry 4.0 adop	Empirical	Competition and technology drive ad	RMS focus missing

Ghobakhloo (2	Barriers	Industry 4.0 chall	Review	High cost, skill gap barriers	Lack of RMS-specific analy
Zhong et al. (2	Technologies	Smart manufactu	Review	Digital integration improves efficiency	RMS integration limited
Morgan et al. (	Technologies	Smart RMS (SR*	Review	RMS evolving with and AI integration	Lack of structured adoption frameworks

The thematic analysis of the literature reveals that research on RMS and Industry 4.0 can be broadly categorized into three major dimensions: drivers, barriers, and enabling technologies. Technological advancements such as IoT, CPS, artificial intelligence, and digital twin systems are the primary enablers of smart manufacturing and RMS integration. Recent studies (Li et al., 2024; Arnarson et al., 2024) emphasize the convergence of RMS with intelligent systems, leading to the development of autonomous and adaptive manufacturing environments.On the other hand, several barriers hinder the adoption of RMS, including high investment costs, lack of skilled workforce, cybersecurity risks, and integration challenges with legacy systems. Contemporary research (Patel et al., 2025; Windmann et al., 2024) highlights that these barriers are becoming more complex due to the increasing digitalization of manufacturing systems.Furthermore, drivers such as market demand for customization, competitive pressure, and government support play a significant role in accelerating adoption. Studies indicate that the integration of RMS with Industry 4.0 technologies enhances flexibility, efficiency, and sustainability, making it a critical component of next-generation manufacturing systems.

3. Research Methodology

This study adopts a **systematic literature review (SLR) methodology** to analyze the adoption of Reconfigurable Manufacturing Systems within the context of Industry 4.0. The SLR approach is widely recognized as a rigorous and transparent method for identifying, evaluating, and synthesizing existing research, ensuring reliability and minimizing bias (Tranfield et al., 2003; Kitchenham, 2004). This methodology is particularly suitable for exploring emerging research domains where knowledge is fragmented and requires structured consolidation.The research methodology is structured into four major stages: **literature identification, screening and selection, data**

extraction, and analysis/synthesis. In the first stage, a comprehensive search strategy was developed using major academic databases such as Scopus, Web of Science, ScienceDirect, and Google Scholar. Relevant keywords including “Reconfigurable Manufacturing Systems,” “Industry 4.0,” “smart manufacturing,” “digital transformation,” “drivers,” and “barriers” were used in combination with Boolean operators (AND, OR) to retrieve high-quality and relevant studies. This ensured broad coverage of interdisciplinary research related to RMS and Industry 4.0.In the second stage, the collected studies were screened using predefined inclusion and exclusion criteria. Only peer-reviewed journal articles, conference papers, and review articles published in English were considered. Studies focusing on RMS design, Industry 4.0 technologies, adoption factors, and integration challenges were included, while unrelated articles, duplicate records, and non-academic sources were excluded. This filtering process enhanced the validity and relevance of the selected literature.The third stage involved **data extraction and classification**, where key information from selected studies was systematically organized into categories such as technological advancements, system characteristics, drivers, barriers, and integration aspects. Special emphasis was given to recent and high-impact studies, including the comprehensive review by Morgan et al. (2021), which provides detailed insights into smart reconfigurable manufacturing systems, machine intelligence, and distributed control architectures in Industry 4.0 environments.In the final stage, **qualitative content analysis and thematic synthesis** were conducted to identify patterns, relationships, and research gaps. The findings were grouped into three major themes: drivers, barriers, and enabling technologies. Additionally, to strengthen the analytical perspective, the study conceptually incorporates structured modeling approaches such as **Interpretive Structural Modelling (ISM)** (Warfield, 1974) and **MICMAC analysis** (Mandal & Deshmukh, 1994), which are widely used for analyzing complex interrelationships among factors in manufacturing systems. These methods support the hierarchical structuring and classification of variables based on their driving and dependence power.Overall, this systematic methodology ensures a **comprehensive, transparent, and structured review process**, enabling the identification of critical factors influencing RMS adoption in Industry 4.0 and providing a strong foundation for future research and framework development.

4. Drivers of RMS Adoption in Industry 4.0

The adoption of Reconfigurable Manufacturing Systems (RMS) in Industry 4.0 environments is influenced by a combination of technological, economic, market, and organizational drivers. These drivers play a crucial role in enabling manufacturing systems to become more flexible, efficient, and responsive to dynamic industrial requirements.One of the most significant drivers of RMS adoption is **technological advancement**, particularly the integration of Industry 4.0 technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), and cyber-physical systems (CPS). These technologies enable real-time monitoring, predictive maintenance, and intelligent decision-making in manufacturing systems (Lee et al., 2015; Lasi et al., 2014). The ability of RMS to seamlessly integrate with these digital technologies enhances system adaptability and operational efficiency, making it a key enabler of smart manufacturing (Zhong et al., 2017).Another important driver is the increasing **market demand for mass customization and product variety**. Modern consumers demand highly customized products with shorter life cycles, which requires manufacturing systems to be flexible and responsive. RMS provides customized flexibility by allowing rapid reconfiguration of production systems to accommodate different product variants (Koren et al., 1999). This capability enables manufacturers to meet changing customer demands without significant increases in cost or downtime (Pine, 1993).**Competitive pressure** in global markets also acts as a strong driver for RMS adoption. Organizations are continuously striving to improve productivity, reduce costs, and enhance product quality to maintain competitiveness. RMS supports these objectives by enabling efficient resource utilization and minimizing production downtime (Kamble et al., 2018). The ability to quickly adapt to market changes provides a strategic advantage to firms operating in highly competitive environments.Economic factors, particularly **cost efficiency and long-term financial benefits**, further encourage the adoption of RMS. Although RMS requires a relatively high initial investment, its modular and scalable nature allows manufacturers to reuse existing components and avoid complete system replacement when product designs change. This reduces lifecycle costs and improves return on investment (Koren & Shpitalni, 2010). Additionally, improved productivity and reduced waste contribute to overall cost savings.**Government policies and industrial initiatives** also play a crucial role in promoting RMS adoption. Programs such as digital transformation strategies and manufacturing modernization initiatives encourage industries to adopt advanced technologies. Supportive policies, financial incentives, and infrastructure development create a favorable environment for implementing RMS, particularly in developing economies (Kamble et al., 2018).Furthermore, the need for **sustainable manufacturing practices** has emerged as a significant driver. Industries are increasingly focusing on reducing environmental impact, optimizing resource utilization, and improving energy efficiency. RMS contributes to sustainability by enabling precise control over production processes and minimizing waste (ElMaraghy, 2005). This aligns with global sustainability goals and regulatory requirements.In addition, **operational flexibility and scalability requirements** act as key drivers for RMS adoption. Manufacturing systems must be capable of adjusting production capacity in response to demand fluctuations. RMS achieves this through its modular structure, allowing the addition or removal of system components without disrupting the entire production line (Mehrabi et al., 2000). This flexibility enhances system responsiveness and reduces downtime.Overall, the adoption of RMS is driven by a combination of technological innovation, market dynamics, economic benefits, and policy support. These drivers collectively enable industries to transition towards smart, flexible, and sustainable manufacturing systems within the framework of Industry 4.0.

5. Barriers to RMS Adoption in Industry 4.0

Despite the significant advantages offered by Reconfigurable Manufacturing Systems (RMS), their adoption in Industry 4.0 environments is constrained by several technological, economic, and organizational barriers. These barriers limit the effective implementation of RMS, particularly in developing economies and small- and medium-sized enterprises (SMEs).One of the most critical barriers is the **high initial investment cost** associated with RMS implementation. Establishing a reconfigurable manufacturing system requires advanced machinery, modular components, and integration of digital technologies such as IoT and AI. For many organizations, especially SMEs, these upfront costs create financial constraints and discourage adoption (Ghobakhloo, 2020). Although RMS offers long-term benefits, the high capital requirement remains a major deterrent.Another significant barrier is the **lack of skilled workforce and technical expertise**. RMS requires specialized knowledge in system design, automation, data analytics, and digital integration.

Many industries face a shortage of trained personnel capable of managing such advanced systems, which slows down implementation and affects system performance (Kamble et al., 2018). This skills gap is particularly prominent in developing countries where training infrastructure is limited.The **integration of RMS with existing legacy systems** also presents a major challenge. Many manufacturing organizations still rely on traditional equipment and outdated technologies that are not compatible with modern reconfigurable systems. Integrating RMS with these legacy systems involves complex modifications, interoperability issues, and additional costs, making the transition difficult (Kamble et al., 2018).In addition, **technological complexity and system design challenges** act as barriers to RMS adoption. Designing modular and scalable systems requires advanced engineering capabilities and careful planning. The coordination between hardware and software components, along with system synchronization, adds to the complexity of implementation (Mehrabi et al., 2000).**Cybersecurity risks and data privacy concerns** have also emerged as critical barriers in Industry 4.0 environments. The increased connectivity of manufacturing systems exposes them to potential cyber threats, which can compromise operational safety and data integrity. Organizations are often reluctant to adopt highly connected systems without robust security frameworks (Lee et al., 2015).Another important barrier is **organizational resistance to change**. Employees and management may be hesitant to adopt new technologies due to fear of job displacement, lack of awareness, or uncertainty about system benefits. This resistance can delay decision-making and hinder the successful implementation of RMS (Sony & Naik, 2019).Furthermore, **lack of standardization and interoperability issues** across different technologies and platforms create additional challenges. The absence of uniform standards makes it difficult to integrate various components and systems seamlessly, leading to inefficiencies and increased implementation costs (Xu et al., 2018).Lastly, **financial and policy-related constraints** also influence RMS adoption. Limited access to funding, lack of government incentives, and insufficient infrastructure support can restrict the adoption of advanced manufacturing technologies, especially in emerging economies.

Overall, these barriers highlight the complexity of implementing RMS in Industry 4.0 environments. Addressing these challenges requires strategic planning, workforce development, technological standardization, and supportive policy frameworks to enable successful adoption.

Table3: Comparison of Drivers and Barriers of RMS Adoption in Industry 4.0

Category	Drivers of RMS Adoption	Barriers to RMS Adoption	Impact on RMS Implementation	Key References
Technological Fact	Integration of IoT, AI, enables real-time mon and smart manufacturi	Integration issues wi legacy systems; technological comple	Determines system adaptability and implementation feasibi	Lee et al. (2015); Lasi et al (2014); Mehrabi et al. (20(Kamble et al. (2018)

Market Factors	Demand for mass customization and sho product life cycles	Market uncertainty a demand variability challenges planning	Drives need for flexibil increases system compl	Koren et al. (1999); Pine (1
Economic Factors	Long-term cost efficie improved productivity ROI	High initial investme and financial constra	Influences decision-ma and adoption rate	Koren & Shpitalni (2010); Ghobakhloo (2020)
Organizational Fac	Government support, d transformation initiati management support	Resistance to change of awareness, poor management commit	Affects readiness and implementation succes	Kamble et al. (2018); Sony Naik (2019)
Human Resource F	Skilled workforce ena efficient system operat	Lack of skilled labor technical expertise	Directly impacts systen performance and sustainability	Kamble et al. (2018)
Operational Facto	Scalability and modula improve flexibility and responsiveness	System design comp and coordination cha	Affects system efficien downtime	Mehrabi et al. (2000); ElM (2005)
Security Factors	Digitalization improve monitoring and contro	Cybersecurity risks a data privacy concern	Influences trust and sys reliability	Lee et al. (2015)
Policy & Infrastru	Government policies a Industry 4.0 initiatives support adoption	Lack of infrastructu funding, and policy s in developing econo	Determines adoption feasibility at national/in level	Kamble et al. (2018); Ghob (2020)

The comparison between drivers and barriers highlights that while technological advancements, market demand, and economic benefits strongly promote the adoption of Reconfigurable Manufacturing Systems (RMS), several constraints such as high initial investment, lack of skilled workforce, and integration challenges hinder their effective implementation. Technological drivers enhance system flexibility and intelligence, whereas technological barriers increase complexity and implementation difficulty. Similarly, economic drivers focus on long-term cost benefits, while financial barriers restrict initial adoption. This dual nature of influencing factors indicates that successful RMS implementation depends on maximizing enabling drivers while minimizing inhibiting barriers through strategic planning and policy support.

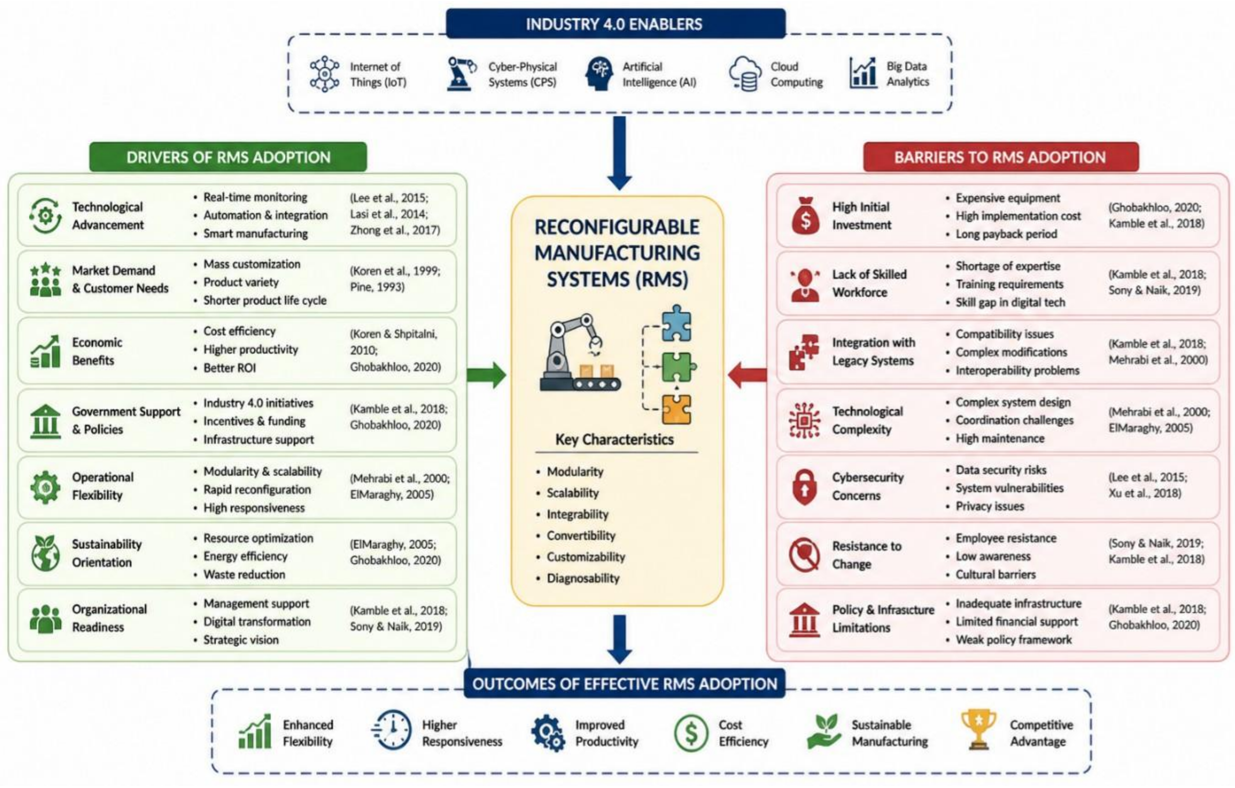

Figure 1: Conceptual Framework for Drivers and Barriers Influencing RMS Adoption in Industry 4.0

6. Integration of RMS with Industry 4.0

The integration of Reconfigurable Manufacturing Systems (RMS) with Industry 4.0 technologies represents a significant advancement in modern manufacturing, enabling the development of intelligent, adaptive, and highly efficient production systems. RMS provides the physical capability for rapid reconfiguration of production capacity and functionality, while Industry 4.0 offers the digital backbone through technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), cyber-physical systems (CPS), and big data analytics.One of the key aspects of this integration is the role of **IoT-enabled connectivity**, which allows machines, sensors, and systems within RMS to communicate in real time. IoT facilitates continuous data collection from manufacturing processes, enabling dynamic monitoring and control of system performance (Atzori et al., 2010). This real-time data exchange enhances the responsiveness of RMS, allowing rapid adjustments in production configurations based on demand fluctuations.**Cyber-Physical Systems (CPS)** further strengthen the integration by linking physical manufacturing components with computational intelligence. CPS enables real-time synchronization between physical machines and digital models, allowing automated decision-making and system optimization (Lee et al., 2015). When combined with RMS, CPS enhances system diagnosability and adaptability, reducing downtime and improving operational efficiency.The application of **Artificial Intelligence (AI) and Machine Learning (ML)** in RMS plays a crucial role in predictive maintenance, process optimization, and intelligent scheduling. AI-driven algorithms analyze large volumes of data generated by Industry 4.0 systems to identify patterns and predict potential failures (Jordan & Mitchell, 2015). This capability allows RMS to proactively reconfigure itself, ensuring uninterrupted production and improved system reliability.Another important dimension is the integration of **big data analytics and cloud computing**, which enables large-scale data processing and storage. Big data analytics supports informed decision-making by analyzing production trends, resource utilization, and system performance (Wang et al., 2016). Cloud platforms provide scalable infrastructure for managing data across distributed manufacturing systems, facilitating seamless collaboration and coordination (Xu et al., 2018).The concept of **digital twin technology** has also gained prominence in the integration of RMS with Industry 4.0. Digital twins create virtual replicas of physical manufacturing systems, allowing simulation, monitoring, and optimization of processes in real time (Tao et al., 2018). This enhances the capability of RMS to test and implement reconfiguration strategies without disrupting actual production.Furthermore, the integration of RMS with Industry 4.0 contributes to the development of **smart manufacturing systems** characterized by automation, flexibility, and intelligence. According to Zhong et al. (2017), smart manufacturing combines advanced digital technologies with flexible production systems to achieve higher efficiency and adaptability. RMS acts as a core enabler in this environment by providing the necessary structural flexibility.In addition, this integration significantly improves **supply chain agility and coordination**. Industry 4.0 technologies enable real-time information sharing across supply chains, allowing manufacturers to respond quickly to changes in demand and disruptions (Ivanov et al., 2016). RMS complements this by enabling rapid adjustments in production capacity, ensuring alignment between supply and demand.Despite these advantages, the integration of RMS with Industry 4.0 also presents challenges such as system complexity, interoperability issues, and cybersecurity risks. However, overcoming these challenges can lead to the creation of highly responsive, efficient, and sustainable manufacturing systems.

Overall, the synergy between RMS and Industry 4.0 technologies creates a powerful framework for smart manufacturing. While RMS provides the physical flexibility required for dynamic production environments, Industry 4.0 enhances system intelligence through digitalization and automation. This integration is essential for achieving competitiveness and sustainability in modern manufacturing industries.

7. Research Gaps and Future Directions

7.1 Research Gaps

A critical analysis of existing literature on Reconfigurable Manufacturing Systems (RMS) and Industry 4.0 reveals several important research gaps that limit the practical implementation and theoretical advancement of this domain.Firstly, there is a **lack of integrated studies combining RMS with Industry 4.0 drivers and barriers**. Most research on RMS focuses on system design, modularity, scalability, and convertibility (Koren et al., 1999; Mehrabi et al., 2000), whereas Industry 4.0 studies emphasize digital technologies and adoption challenges (Kamble et al., 2018). However, very few studies have explored how Industry 4.0 drivers and barriers specifically influence

RMS adoption.Secondly, the literature shows an **absence of structured analytical frameworks** for evaluating RMS adoption. Although several conceptual discussions exist, there is limited application of decision-making tools such as Interpretive Structural Modeling (ISM), MICMAC, or DEMATEL to analyze relationships among drivers and barriers. This lack of structured modeling restricts the understanding of complex interdependencies between influencing factors.Another significant gap is the **limited empirical validation of theoretical models**. Most existing studies are conceptual or review-based, with insufficient real-world case studies or industrial data analysis. This reduces the applicability of research findings in practical manufacturing environments.Furthermore, there is a **lack of focus on small and medium-sized enterprises (SMEs)**. Since SMEs form a major portion of manufacturing sectors, especially in developing countries like India, their constraints—such as financial limitations and skill shortages—are not adequately addressed in RMS research.In addition, existing studies often analyze technological, economic, and organizational factors **in isolation rather than as an integrated system**. This fragmented approach limits a holistic understanding of RMS adoption in Industry 4.0 environments.Another gap is the **limited consideration of sustainability and environmental aspects** in RMS adoption. While RMS has the potential to support sustainable manufacturing through resource optimization and waste reduction, this dimension is not sufficiently explored in the literature.

Finally, there is a **lack of standardization and benchmarking frameworks** for evaluating RMS performance. Without standardized metrics, it becomes difficult to compare systems across industries and assess their effectiveness.

7.2 Future Research Directions

Based on the identified gaps, several future research directions are proposed to advance the field of RMS adoption in Industry 4.0.One important direction is the **development of integrated frameworks** that combine drivers, barriers, and RMS performance. Future studies should focus on creating comprehensive models that capture the interaction between technological, economic, and organizational factors using advanced methodologies such as ISM, MICMAC, and DEMATEL.Another promising area is the **application of empirical and case-based research**. Researchers should conduct real-world studies across different industries to validate theoretical models and provide practical insights. This will enhance the reliability and industrial relevance of RMS adoption frameworks.The use of **Artificial Intelligence (AI) and Machine Learning (ML) for decision-making and optimization** in RMS is another emerging research direction. AI-based models can help in predictive maintenance, demand forecasting, and dynamic system reconfiguration, thereby improving system performance.Future research should also focus on **SME-oriented adoption models**, addressing challenges such as limited financial resources, lack of expertise, and infrastructure constraints. Developing cost-effective and scalable solutions will facilitate wider adoption of RMS in emerging economies.In addition, there is a need to explore **sustainability-driven RMS frameworks** that integrate environmental, economic, and social dimensions. This includes energy-efficient system design, waste minimization, and circular manufacturing practices.Another key direction is the **development of standardization and benchmarking models** for RMS performance evaluation. Establishing clear metrics and guidelines will help industries assess system efficiency, flexibility, and return on investment.Finally, future studies should investigate the **role of digital twins, cloud manufacturing, and smart supply chains** in enhancing RMS capabilities. The integration of these advanced technologies can significantly improve system intelligence, responsiveness, and scalability.The analysis of existing literature highlights significant gaps in the integration, modeling, and practical validation of RMS adoption in Industry 4.0. Addressing these gaps through structured frameworks, empirical studies, and technological advancements will contribute to the development of more efficient, flexible, and sustainable manufacturing systems.

8. Conclusion

This study provides a comprehensive review of **Reconfigurable Manufacturing Systems (RMS)** within the context of Industry 4.0, focusing on the key drivers and barriers influencing their adoption. The analysis highlights that RMS represents a transformative manufacturing paradigm capable of addressing the limitations of traditional systems by offering modularity, scalability, and customized flexibility. The integration of RMS with advanced Industry 4.0 technologies such as IoT, Artificial Intelligence, cyber-physical systems, and big data analytics enables the development of intelligent, adaptive, and highly efficient manufacturing environments.The findings of this review indicate that several factors act as strong **drivers of RMS adoption**, including technological advancements, increasing demand for mass customization, competitive pressure, economic benefits, and supportive government policies. These drivers facilitate improved system flexibility, responsiveness, and productivity, thereby enhancing the overall competitiveness of manufacturing industries. At the same time, the study identifies critical **barriers** such as high initial investment, lack of skilled workforce, integration challenges with legacy systems, cybersecurity risks, and organizational resistance to change. These barriers significantly hinder the widespread implementation of RMS, particularly in developing economies and small and medium-sized enterprises.Furthermore, the study emphasizes the importance of **integrating RMS with Industry 4.0 technologies**, which enables real-time data-driven decision-making, predictive maintenance, and dynamic system reconfiguration. This integration creates a synergy between physical manufacturing flexibility and digital intelligence, forming the foundation of smart manufacturing systems. However, successful implementation requires overcoming technological, financial, and organizational challenges through strategic planning, workforce development, and policy support.The review also identifies several **research gaps**, including the lack of integrated frameworks, limited empirical validation, and insufficient application of structured analytical models such as ISM and MICMAC. Addressing these gaps is essential for advancing both theoretical understanding and practical implementation of RMS in Industry 4.0 environments.In conclusion, RMS plays a crucial role in enabling flexible, efficient, and sustainable manufacturing systems in the era of Industry 4.0. The successful adoption of RMS depends on maximizing the impact of enabling drivers while minimizing the effects of inhibiting barriers. Future research should focus on developing integrated frameworks, conducting empirical studies, and leveraging emerging technologies to enhance RMS capabilities. This will support industries in achieving higher productivity, sustainability, and global competitiveness in an increasingly dynamic manufacturing landscape.

References

1. Arnarson, B., et al. (2024). Intelligent RMS architecture. *Procedia CIRP*.
2. Atzori, L., Iera, A., & Morabito, G. (2010). The Internet of Things: A survey. *Computer Networks*, 54(15), 2787–2805.
3. Bortolini, M., Ferrari, E., Gamberi, M., Pilati, F., & Regattieri, A. (2017). Assembly system design in Industry 4.0. *IFAC-PapersOnLine*, 50(1), 11873–11878.
4. Brettel, M., Friederichsen, N., Keller, M., & Rosenberg, M. (2014). How virtualization changes manufacturing. *Procedia CIRP*, 23, 37–44.
5. ElMaraghy, H. A. (2005). Flexible and reconfigurable manufacturing systems paradigms. *International Journal of Flexible Manufacturing Systems*, 17, 261–276.
6. Ghobakhloo, M. (2020). Industry 4.0, digitization, and opportunities for sustainability. *Journal of Cleaner Production*, 252, 119869.
7. Haller, S., et al. (2025). Digital manufacturing systems. *Journal of Intelligent Manufacturing*.
8. Ivanov, D., Sokolov, B., & Dolgui, A. (2016). The ripple effect in supply chains: Trade-off between efficiency, flexibility, and resilience. *International Journal of Production Research*, 54(1), 215–227.
9. Jordan, M. I., & Mitchell, T. M. (2015). Machine learning: Trends, perspectives, and prospects. *Science*, 349(6245), 255–260.
10. Kagermann, H., Wahlster, W., & Helbig, J. (2013). *Recommendations for implementing the strategic initiative INDUSTRIE 4.0*.
11. Kamble, S. S., Gunasekaran, A., & Sharma, R. (2018a). Analysis of Industry 4.0 adoption. *International Journal of Production Research*, 56(3), 1037–1055.
12. Kamble, S. S., Gunasekaran, A., & Sharma, R. (2018b). Analysis of the driving and dependence power of barriers to adopt Industry 4.0 in Indian manufacturing industry. *Computers in Industry*, 101, 107–119.
13. Kitchenham, B. (2004). Procedures for performing systematic reviews.
14. Koren, Y., Heisel, U., Jovane, F., Moriwaki, T., Pritschow, G., Ulsoy, A. G., & Van Brussel, H. (1999). Reconfigurable manufacturing systems. *CIRP Annals*, 48(2), 527–540.
15. Lee, J., Bagheri, B., & Kao, H. A. (2015). A cyber-physical systems architecture for Industry 4.0-based manufacturing systems. *Manufacturing Letters*, 3, 18–23.
16. Li, X., et al. (2024). Smart reconfigurable manufacturing systems. *Procedia CIRP*.
17. Lu, Y. (2017). Industry 4.0: A survey on technologies, applications, and open research issues. *Journal of Industrial Information Integration*, 6, 1–10.
18. Mandal, A., & Deshmukh, S. G. (1994). Vendor selection using interpretive structural modeling (ISM). *International Journal of Operations & Production Management*.
19. Mehrabi, M. G., Ulsoy, A. G., & Koren, Y. (2000). Reconfigurable manufacturing systems: Key to future manufacturing. *Journal of Intelligent Manufacturing*, 11(4), 403–419.
20. Milisavljevic-Syed, J., et al. (2024). Sustainable RMS. *International Journal of Production Research*.
21. Morgan, J., Halton, M., Qiao, Y., & Breslin, J. G. (2021). Smart RMS. *Journal of Manufacturing Systems*, 59, 481–506.
22. Mourtzis, D., Doukas, M., & Bernidaki, D. (2016). Simulation in manufacturing: Review and challenges. *Procedia CIRP*, 25, 213–229.

23. Patel, R., et al. (2025). Industry 4.0 barriers. *Journal of Manufacturing Processes*.
24. Pine, B. J. (1993). *Mass customization: The new frontier in business competition*. Harvard Business School Press.
25. Ramu, S. (2024). Industry 4.0 impact study. *Journal of Engineering Business*.
26. Sony, M., & Naik, S. (2019). Industry 4.0 integration challenges. *Journal of Manufacturing Technology Management*.
27. Tao, F., Zhang, M., Liu, Y., & Nee, A. Y. C. (2018). Digital twin driven smart manufacturing. *Journal of Manufacturing Systems*, 48, 157–169.
28. Tordeux, A., et al. (2024). Predictive maintenance systems. *Reliability Engineering & System Safety*.
29. Tranfield, D., Denyer, D., & Smart, P. (2003). Towards a methodology for developing evidence-informed management knowledge. *British Journal of Management*, 14(3), 207–222.
30. Wang, S., Wan, J., Li, D., & Zhang, C. (2016). Implementing smart factory of Industry 4.0: An outlook. *International Journal of Distributed Sensor Networks*, 12(1), 1–10.
31. Warfield, J. N. (1974). Developing interconnection matrices in structural modeling. *IEEE Transactions on Systems, Man, and Cybernetics*.
32. Windmann, S., et al. (2024). AI challenges in Industry 4.0. *IEEE Access*.
33. World Scientific. (2024). RMS and Industry 4.0 integration. *International Journal of Production Economics*.
34. Xu, X., Xu, X., & Li, L. (2018). Cloud manufacturing: State-of-the-art and future trends. *Robotics and Computer-Integrated Manufacturing*, 54, 1–10.
35. Zhong, R. Y., Xu, X., Klotz, E., & Newman, S. T. (2017). Intelligent manufacturing in the context of Industry 4.0. *Engineering*, 3(5), 616–630.
36. Zhou, K., Liu, T., & Zhou, L. (2015). Industry 4.0: Towards future industrial opportunities. *Proceedings of IEEE*.